NCHRP Project 18-15
High Performance/High-Strength Lightweight Concrete for Bridge Girders and Decks

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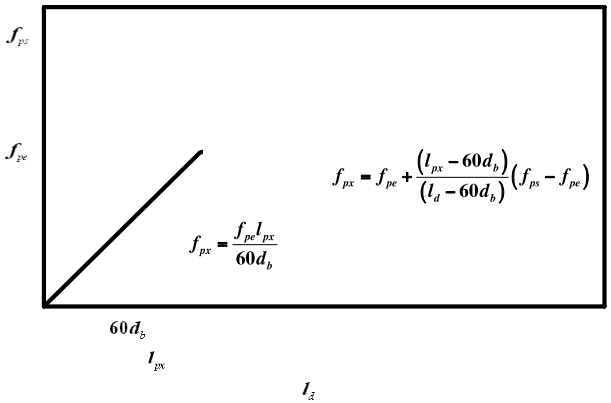
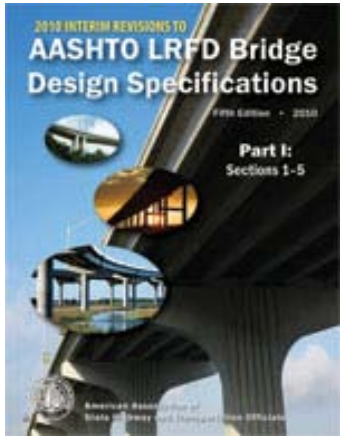
Objectives and Scope

- Objectives
  - Investigate key design parameters when using LWC in HP/HS girders and decks
  - Recommend changes to the AASHTO LRFD Bridge Design and Construction Specifications





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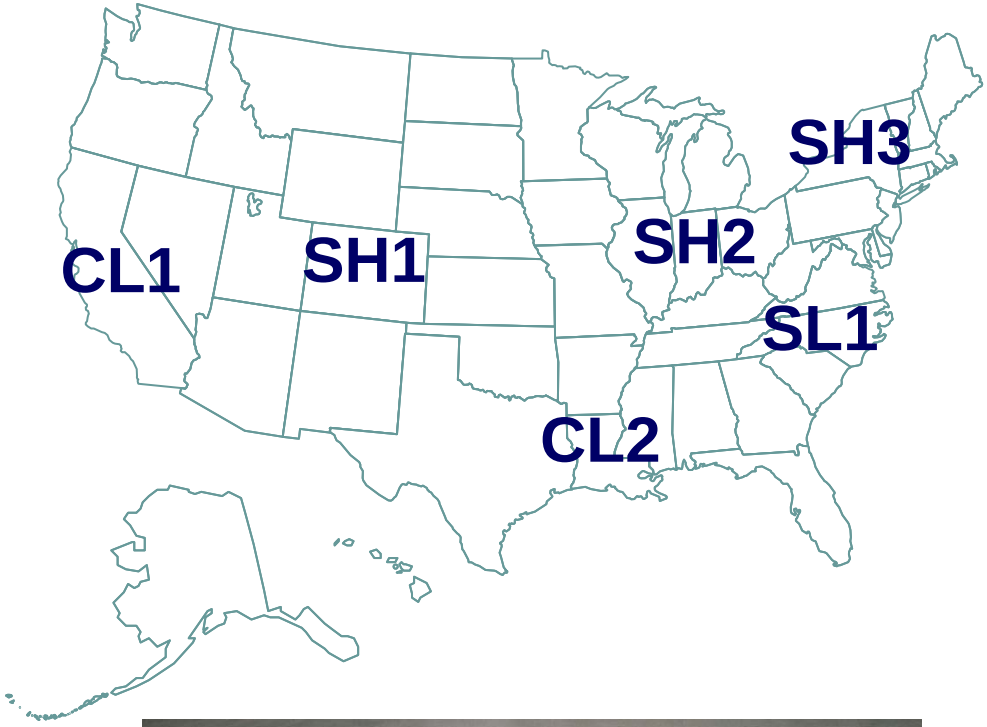

- Scope
  - Lightweight CA
    - SH – Shale
    - CL – Clay
    - SL – Slate
  - Normal weight FA
  - Equilibrium density of not more than 125 pcf

Material Property Results

- Compressive Strength, f'_c (ksi)

Cement. Material lb/yd^3	Aggregate	OPC	OPC + 20% FA	OPC + 40% Slag	OPC + 7% SF
752 (0.40 w/cm)	CL1	5.54	4.61	4.58	
	CL2	6.17	5.46	6.00	
	SH1	6.26	5.48	6.18	
	SH2	6.10	5.32	6.18	
	SH3	5.83	5.82	5.93	
	SL1	7.18	6.24	7.03	
800 (0.30 w/cm)	CL1	6.21	6.16	6.63	6.27
	CL2	7.37	6.92	7.58	7.43
	SH1	7.50	7.24	7.48	7.31
	SH2	7.00	6.59	7.33	7.12
	SH3	8.45	7.90	8.55	8.90
	SL1	9.00	8.50	9.77	9.35
850 (0.30)	SL1	8.74		9.38	9.43
900 (0.30)	SL1		8.61	9.83	

$f'_{c\ design}$ = 4 ksi

$f'_{c\ design}$ = 8 ksi

$f'_{c\ design}$ = 10 ksi

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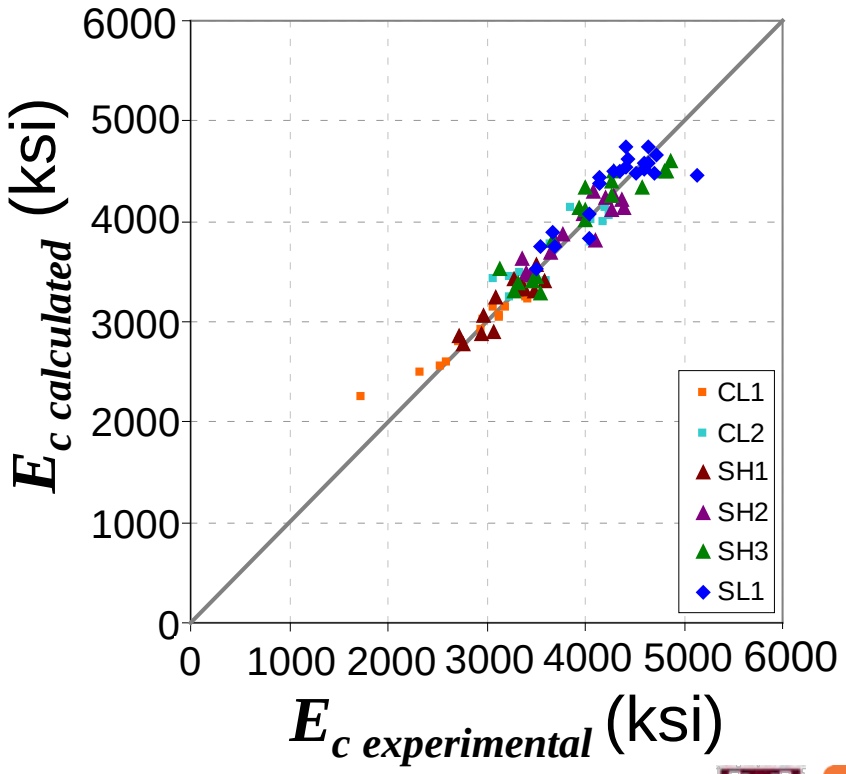
Material Property Results

- Modulus of Elasticity

$$E_c = 33{,}000 K_1 w_c^{1.5} \sqrt{f'_c}$$

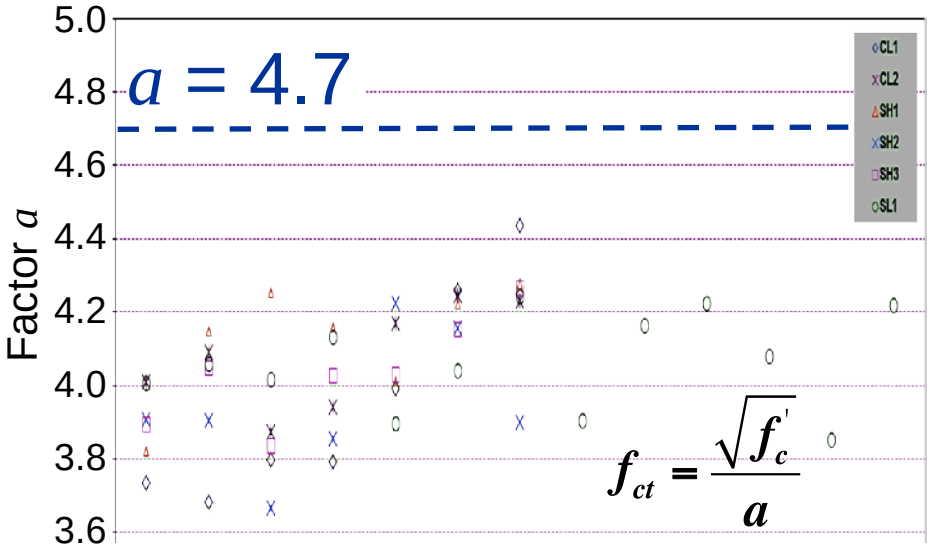
Aggregate	K_1
CL1	0.87
CL2	1.06
SH1	0.87
SH2	1.08
SH3	1.00
SL1	1.06
All Lightweight	**1.00**



Material Property Results

- Modifier for sand-LWC

$$4.7 f_{ct} \leq \sqrt{f_c^{'}} \ , \ 0.85\sqrt{f_c^{'}}$$

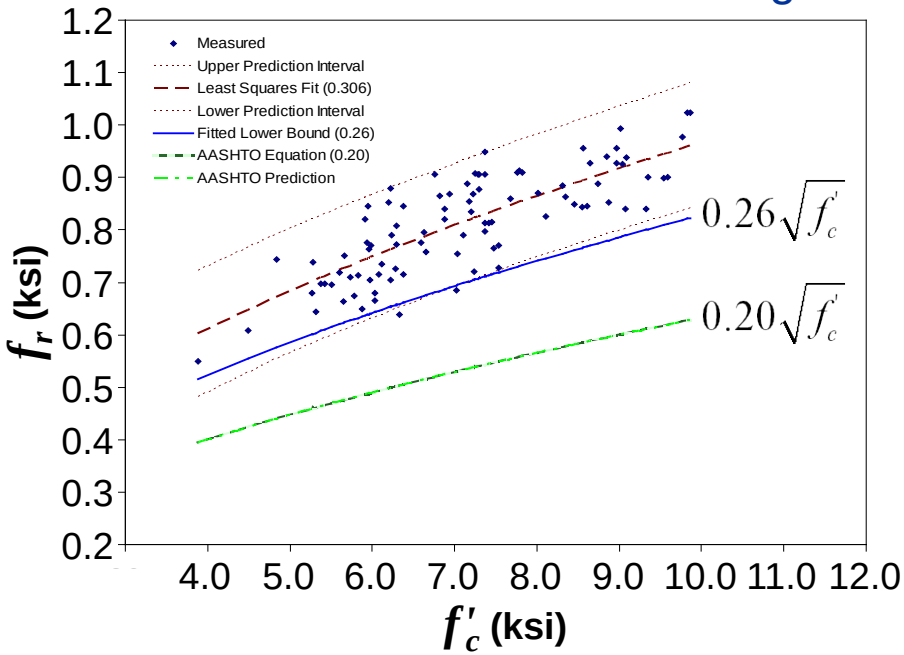


Split Cylinder Tests for Various Mix Designs

- Effectively, need for modifier is eliminated

- Modulus of Rupture (AASHTO 5.4.2.6)

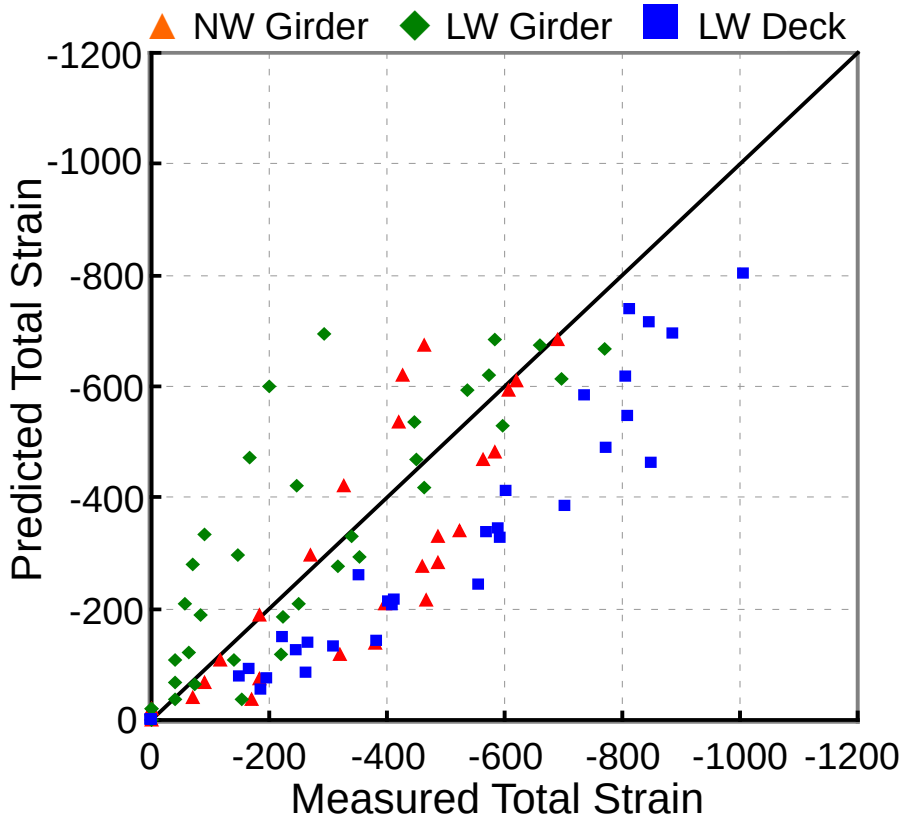
MoR Tests for Various Mix Designs



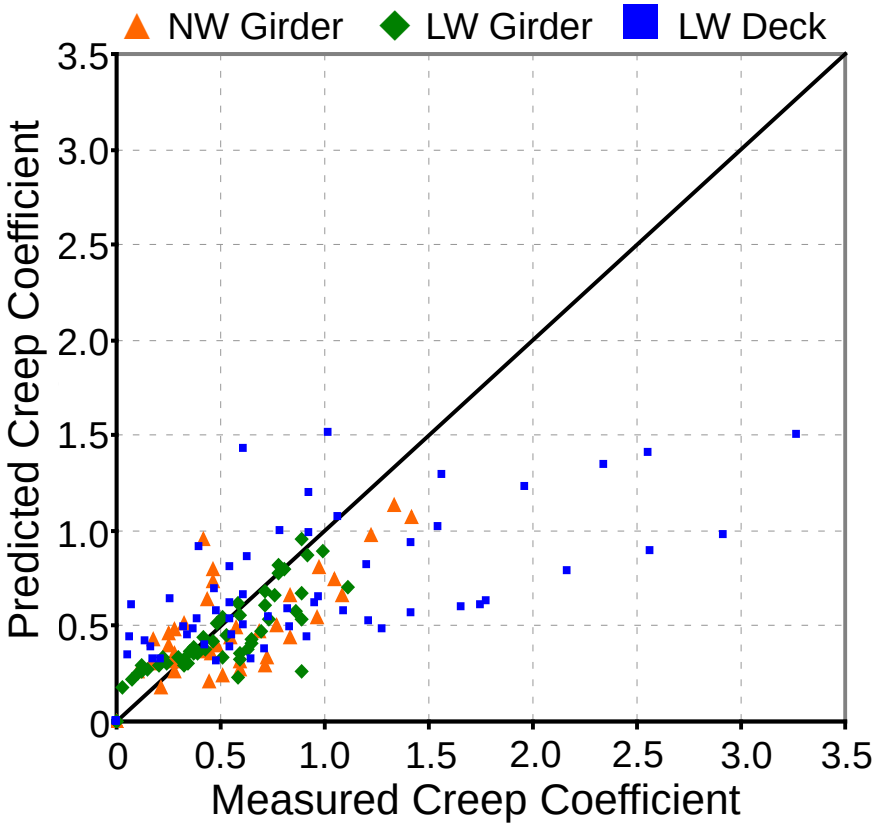
- MoR can be the same as NWC

Material Property Results

- Shrinkage



- Creep

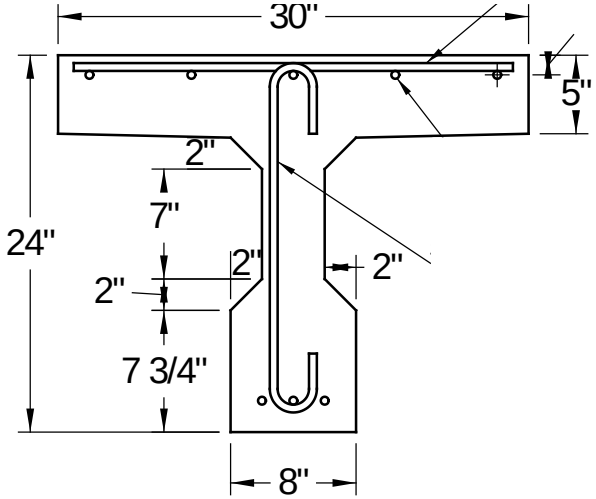


AASHTO is a better predictor than ACI 209 or CEB MC90, except for creep in decks

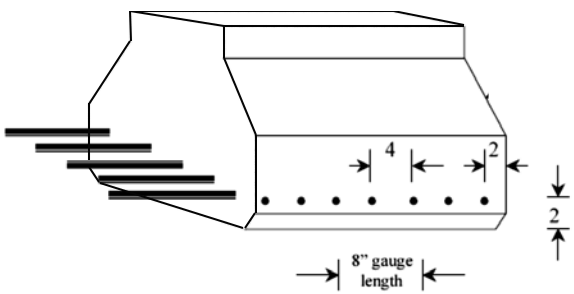
Structural Testing

- Transfer & Development Length

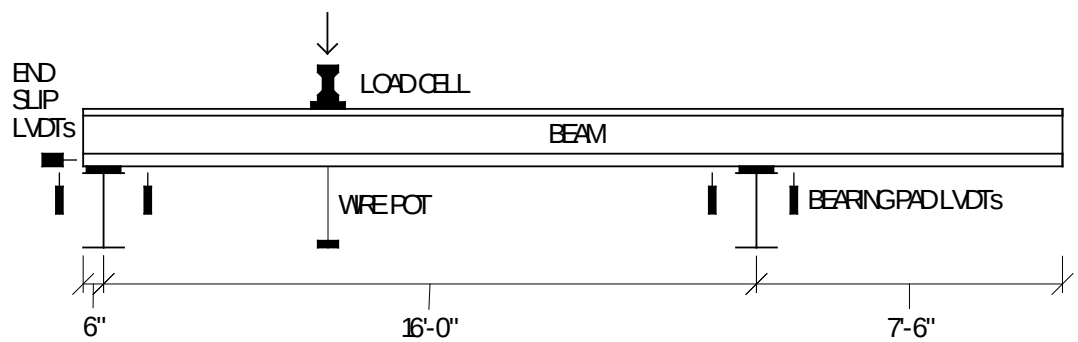
Specimen Detail



Test	AASHTO	Ramirez & Russell
ℓ_t	$60 d_b$	$\frac{120}{\sqrt{f'_{ci}}} d_b \geq 40 d_b$
ℓ_d	$\kappa\left(f_{ps} - \frac{2}{3} f_{pe}\right) d_b$	$\left(\frac{120}{\sqrt{f'_{ci}}} + \frac{225}{\sqrt{f'_c}}\right) d_b \geq 100 d_b$



Testing for ℓ_t

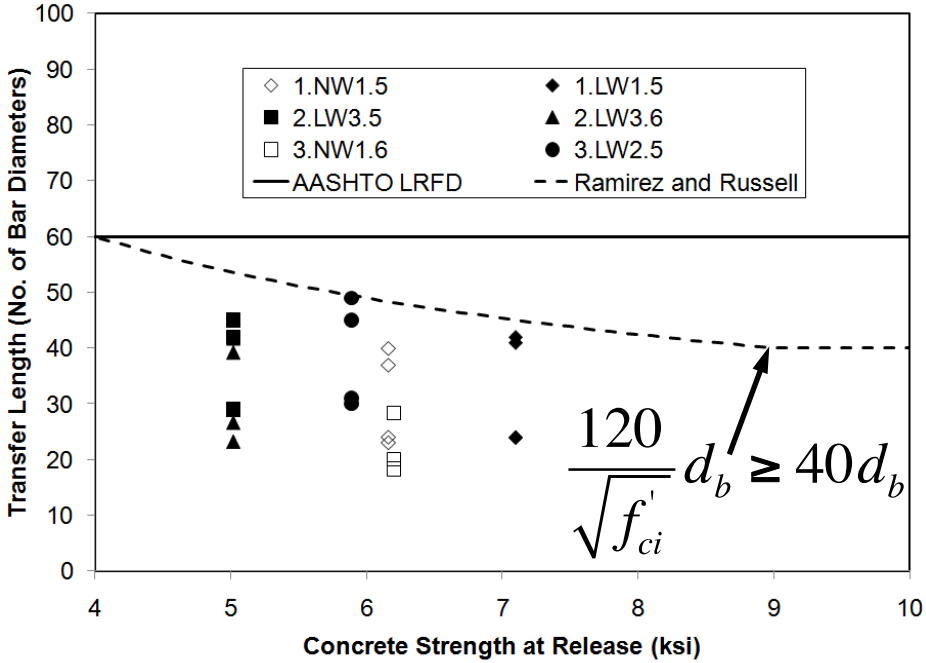


Testing for ℓ_d

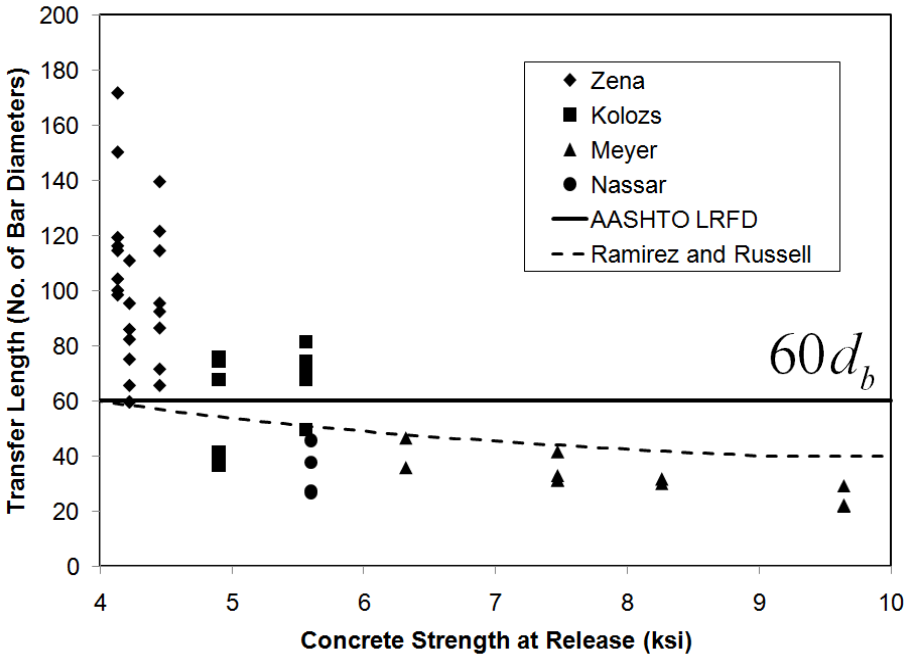
Structural Testing

- Transfer Length

NCHRP Study



Previous Research



Both AASHTO and Ramirez & Russell provide a reasonable upper bound for LWC

Structural Testing

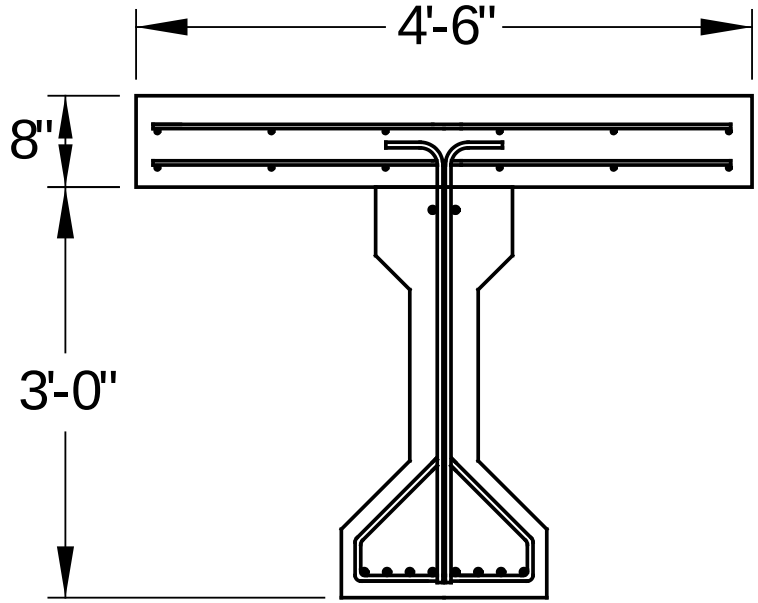
- Development Length

Specimen ID	Experimental Range (in.)		AASHTO (in.)	Ramirez & Russell (in.)
	Lower	Upper		
1.NW1.5		51	77	64
1.LW1.5		49	79	61
2.LW3.5	53	56	83	66
3.LW3.5	47	51	80	62
3.NW1.6	51	56	94	76
2.LW3.6	65	68	100	79

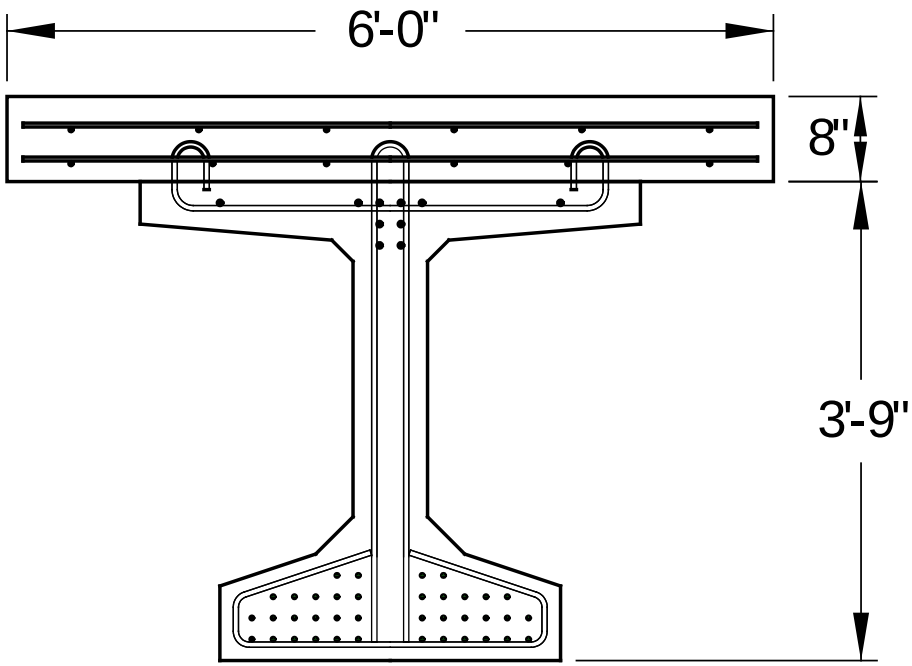
Both AASHTO and Ramirez & Russell provide a reasonable upper bound for LWC

Structural Testing

- Shear Strength
  - Cross-sections



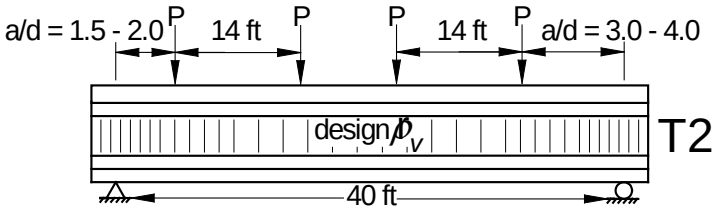
AASHTO Type II



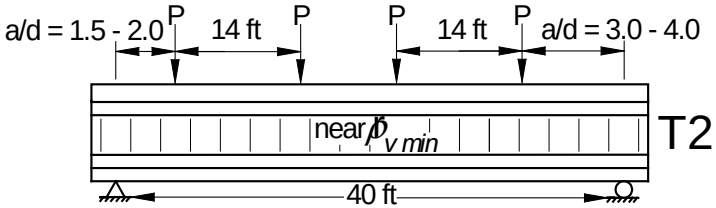
PCBT-45

Structural Testing

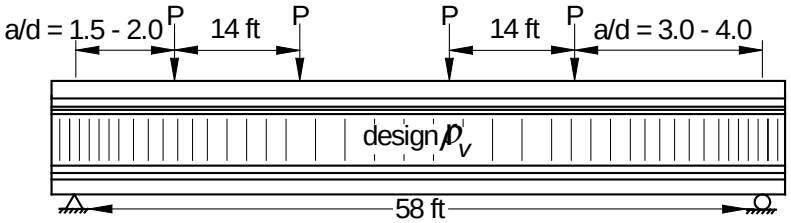
- Shear Strength
  - Test Variables
    - A_c
    - γ_c, f'_c
    - d_v, a/d
    - reinforcement



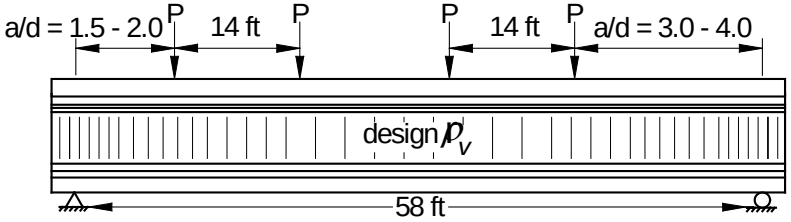
T2.8.Typ



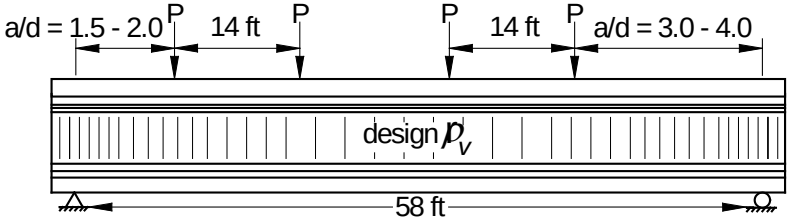
T2.8.Min



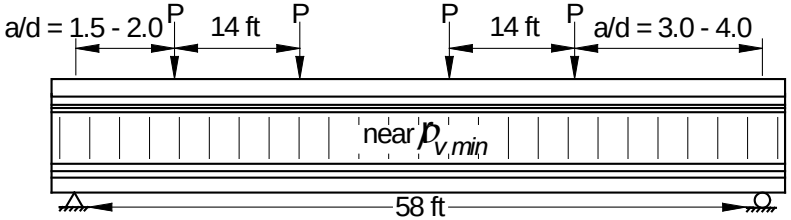
BT.8N.Typ



BT.8.Typ



BT.10.Typ



BT.10.Typ

Structural Testing

- Shear Strength
  - Results

Test ID	w_c (pcf)	f_c (ksi)	a/d
T2.8.Typ.1	125.4	8.9	1.5
T2.8.Typ.2	125.4	8.9	3.1
T2.8.Min.1	125.4	8.9	1.5
T2.8.Min.2	125.4	9.0	2.9
BT.8.Typ.1	126.5	9.1	2.0
BT.8.Typ.2	126.5	9.1	3.1
BT.8N.Typ.1	150.0	8.5	2.1
BT.8N.Typ.2	150.0	8.6	3.0
BT.10.Typ.1	125.0	8.9	2.0
BT.10.Typ.2	125.0	9.9	2.9
BT.10.Min.1	126.0	9.7	2.1
BT.10.Min.2	127.4	10.3	3.0

Structural Testing

- Shear Strength
  - Results

Test ID	w_c (pcf)	f_c (ksi)	a/d
T2.8.Typ.1	**125.4**	8.9	1.5
T2.8.Typ.2	**125.4**	8.9	3.1
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T2.8.Min.2	**125.4**	9.0	2.9
BT.8.Typ.1	**126.5**	9.1	2.0
BT.8.Typ.2	**126.5**	9.1	3.1
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Structural Testing

- Shear Strength

Test ID	Failure Mode(s)	V_{Exp} (kip)	General Procedure *A. 5.8.3.4.2*		Simplified Procedure *A. 5.8.3.4.3*	
			$^{Exp}/_{Gen.}$	$^{Exp}/_{Gen}$ No λ_v	$^{Exp}/_{Sim}$	$^{Exp}/_{Sim}$ No λ_v
T2.8.Typ.1	Flexural / Slip	361	1.70	1.66	1.14	1.12
T2.8.Typ.2	Flexural	292	1.49	1.47	1.01	0.99
T2.8.Min.1	Web Shear / Slip	382	2.07	2.02	1.45	1.42
T2.8.Min.2	——	308	1.72	1.69	1.20	1.18
BT.8.Typ.1	Web Shear / Slip	500	1.63	1.60	1.34	1.34
BT.8.Typ.2	Flexural	407	1.46	1.43	1.20	1.22
BT.8N.Typ.1	Web Shear / Slip	431	1.66	—	1.36	—
BT.8N.Typ.2	Web Shear / Slip	382	1.58	—	1.32	—
BT.10.Typ.1	Web Shear / Slip	518	1.82	1.78	1.53	1.49
BT.10.Typ.2	Web Shear / Flex. / Slip	428	1.60	1.57	1.30	1.28
BT.10.Min.1	Web Shear / Slip	475	2.12	2.05	1.97	1.95
BT.10.Min.2	Web Shear	371	1.64	1.60	1.57	1.54
	Average $^{Exp}/_{Calc}$ ratio for LWC		**1.72**	**1.69**	**1.37**	**1.35**
	Average $^{Exp}/_{Calc}$ ratio for NWC		**1.62**	**—**	**1.34**	**—**

Structural Testing

- Shear Strength

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BT.10.Typ.2	**Web Shear / Flex. / Slip**	428	1.60	1.57	1.30	1.28
BT.10.Min.1	**Web Shear / Slip**	475	2.12	2.05	1.97	1.95
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BT.8N.Typ.2	**Web Shear / Slip**	382	**1.58**	—	**1.32**	—
BT.10.Typ.1	**Web Shear / Slip**	518	**1.82**	1.78	**1.53**	1.49
BT.10.Typ.2	**Web Shear / Flex. / Slip**	428	**1.60**	1.57	**1.30**	1.28
BT.10.Min.1	**Web Shear / Slip**	475	**2.12**	2.05	**1.97**	1.95
BT.10.Min.2	**Web Shear**	371	**1.64**	1.60	**1.57**	1.54
	Average $^{Exp}/_{Calc}$ ratio for LWC		**1.72**	**1.69**	**1.37**	**1.35**
	Average $^{Exp}/_{Calc}$ ratio for NWC		**1.62**	**—**	**1.34**	**—**

Structural Testing

- Shear Strength

Test ID	Failure Mode(s)	V_{Exp} (kip)	General Procedure *A. 5.8.3.4.2*		Simplified Procedure *A. 5.8.3.4.3*	
			$^{Exp}/_{Gen.}$	$^{Exp}/_{Gen}$ No λ_v	$^{Exp}/_{Sim}$	$^{Exp}/_{Sim}$ No λ_v
T2.8.Typ.1	Flexural / Slip	361	1.70	1.66	1.14	1.12
T2.8.Typ.2	Flexural	292	1.49	1.47	1.01	0.99
T2.8.Min.1	Web Shear / Slip	382	2.07	2.02	1.45	1.42
T2.8.Min.2	——	308	1.72	1.69	1.20	1.18
BT.8.Typ.1	Web Shear / Slip	500	1.63	1.60	1.34	1.34
BT.8.Typ.2	**Flexural**	**407**	**1.46**	1.43	**1.20**	1.22
BT.8N.Typ.1	Web Shear / Slip	431	1.66	—	1.36	—
BT.8N.Typ.2	**Web Shear / Slip**	**382**	**1.58**	—	**1.32**	—
BT.10.Typ.1	Web Shear / Slip	518	1.82	1.78	1.53	1.49
BT.10.Typ.2	Web Shear / Flex. / Slip	428	1.60	1.57	1.30	1.28
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Structural Testing

- Shear Strength

Test ID	Failure Mode(s)	V_{Exp} (kip)	General Procedure *A. 5.8.3.4.2*		Simplified Procedure *A. 5.8.3.4.3*	
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BT.8N.Typ.1	**Web Shear / Slip**	**431**	**1.66**	—	**1.36**	—
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Structural Testing

- Shear Strength

Test ID	Failure Mode(s)	V_{Exp} (kip)	General Procedure *A. 5.8.3.4.2* $^{Exp}/_{Gen.}$	General Procedure *A. 5.8.3.4.2* $^{Exp}/_{Gen}$ No λ_v	Simplified Procedure *A. 5.8.3.4.3* $^{Exp}/_{Sim}$	Simplified Procedure *A. 5.8.3.4.3* $^{Exp}/_{Sim}$ No λ_v
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BT.8N.Typ.1	Web Shear / Slip	431	1.66	—	1.36	—
BT.8N.Typ.2	Web Shear / Slip	382	1.58	—	1.32	—
BT.10.Typ.1	Web Shear / Slip	518	**1.82**	**1.78**	1.53	1.49
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Structural Testing

- Shear Strength

Test ID	Failure Mode(s)	V_{Exp} (kip)	General Procedure *A. 5.8.3.4.2*		Simplified Procedure *A. 5.8.3.4.3*	
			$^{Exp}/_{Gen.}$	$^{Exp}/_{Gen}$ No λ_v	$^{Exp}/_{Sim}$	$^{Exp}/_{Sim}$ No λ_v
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BT.8.Typ.1	Web Shear / Slip	500	**1.63**	**1.60**	**1.34**	**1.34**
BT.8.Typ.2	Flexural	407	**1.46**	**1.43**	**1.20**	**1.22**
BT.8N.Typ.1	Web Shear / Slip	431	1.66	—	1.36	—
BT.8N.Typ.2	Web Shear / Slip	382	1.58	—	1.32	—
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Structural Testing

- Horizontal Interface Shear Transfer

$$V_{ni} = \min \begin{cases} cA_{cv} + \mu\left(A_{cf} f_y + P_c\right) \\ K_1 f_c^{'} A_{cv} \\ K_2 A_{cv} \end{cases}$$

c = 0.28 ksi

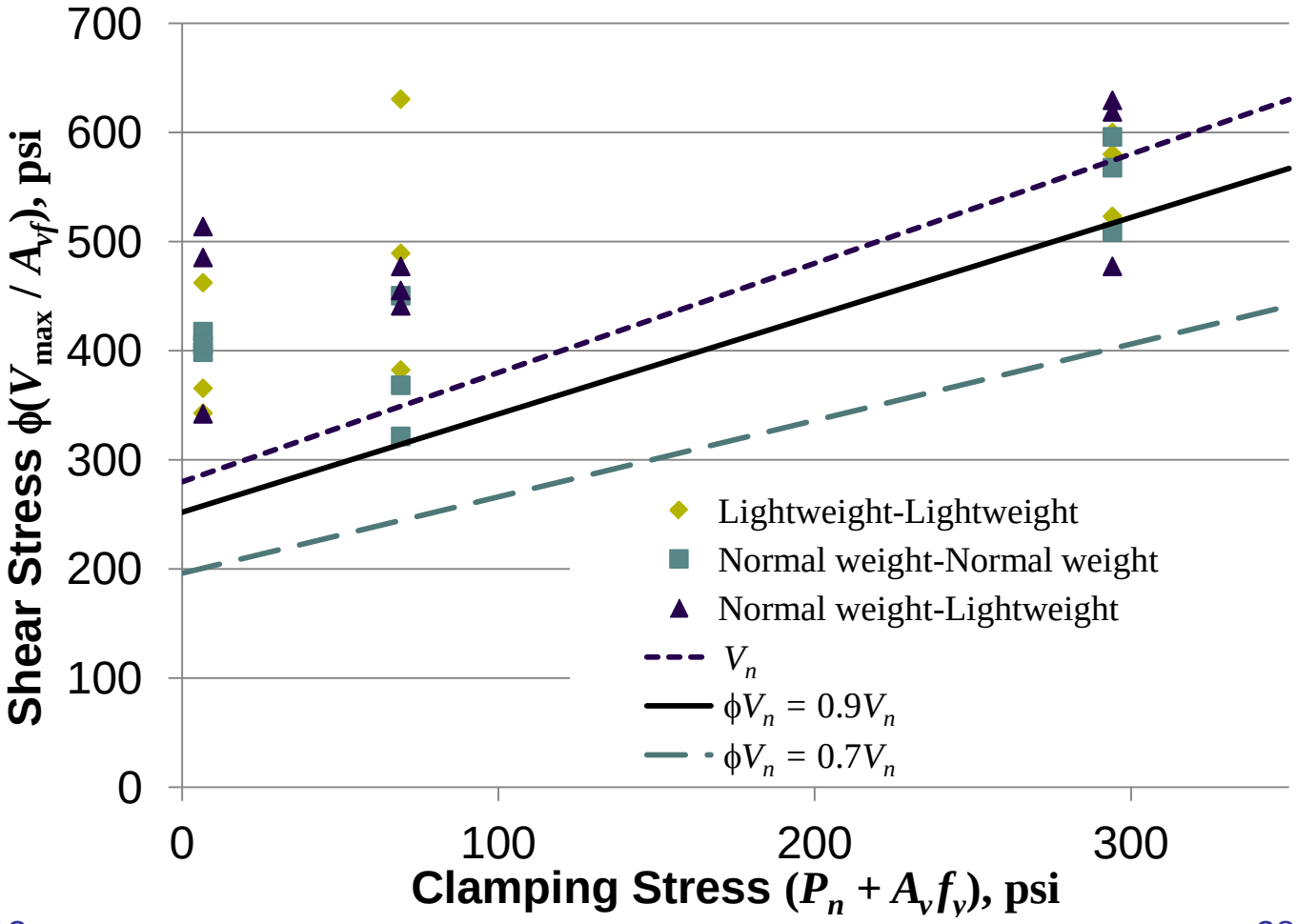
μ = 1.0 $\quad$ K_1 = 0.3

ϕ = 0.90 (NWC) $\quad$ K_2 = 1.8 ksi (NWC)

Article 5.8.4.1 $\quad$ ϕ = 0.70 (LWC) $\quad$ K_2 = 1.3 ksi (LWC)

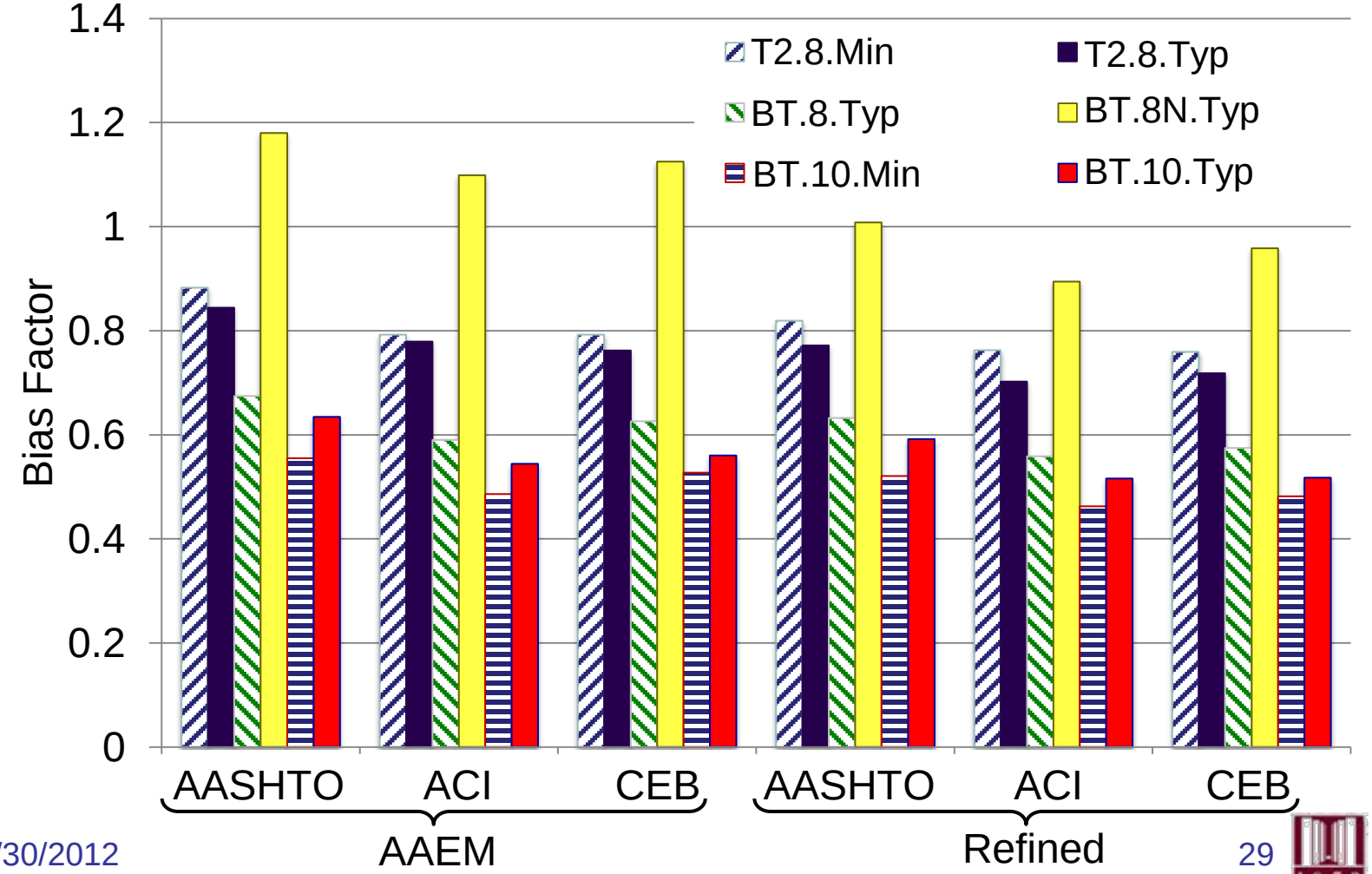
Structural Testing

- Horizontal Interface Shear Transfer



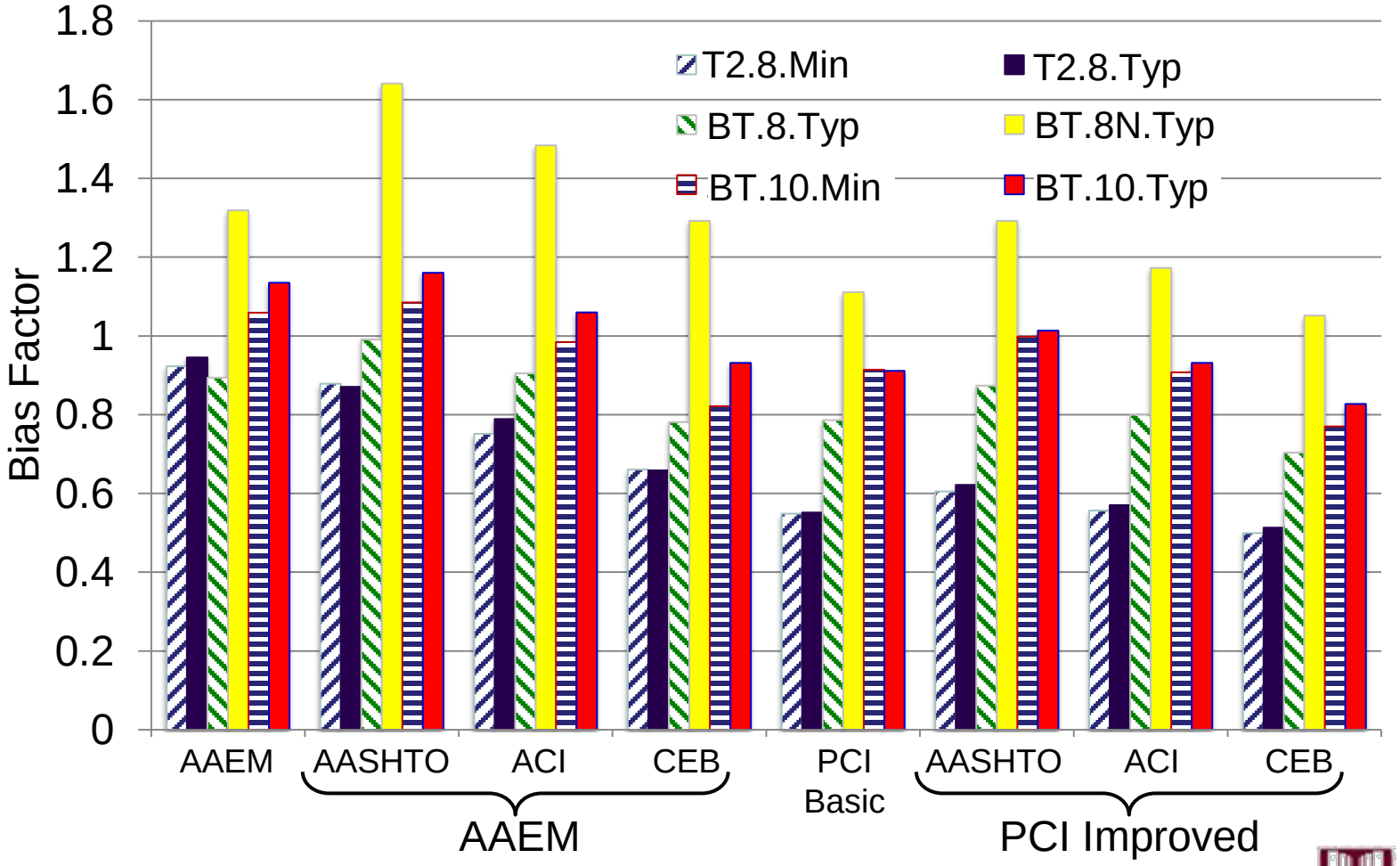
Structural Testing

- Total Prestress Losses



Structural Testing

- Total Camber

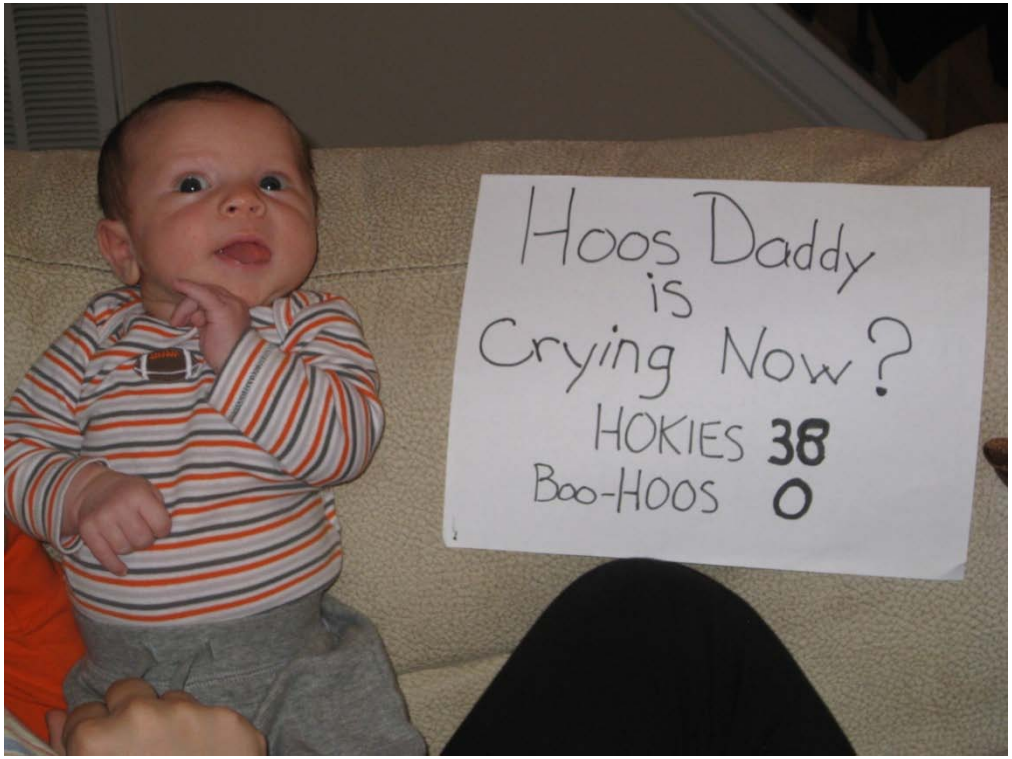


Summary

- Quality concrete using lightweight coarse aggregate can be achieved
  - ✦ Splitting Tensile Strength
  - ✦ MoR
  - ✦ Shrinkage
  - ✦ Creep
  - ✦ Transfer Length
  - ~ Compressive Strength
  - ~ MoE

Summary

- λ_v is not needed
- ϕ_v should be increased from 0.70 to 0.85
  - Beam shear strength
  - Interface shear strength
- Prestress losses were lower than predicted
- Camber was generally less than predicted
- Final report due out in a couple of months

Thank You

Questions?