AASHTOWare™ BRIDGE DESIGN AND RATING

Modified Compression Field Theory (MCFT) Application in BrDR

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WJE / ProMiles

MCFT for BrDR Users

A primer for using MCFT in Load Rating

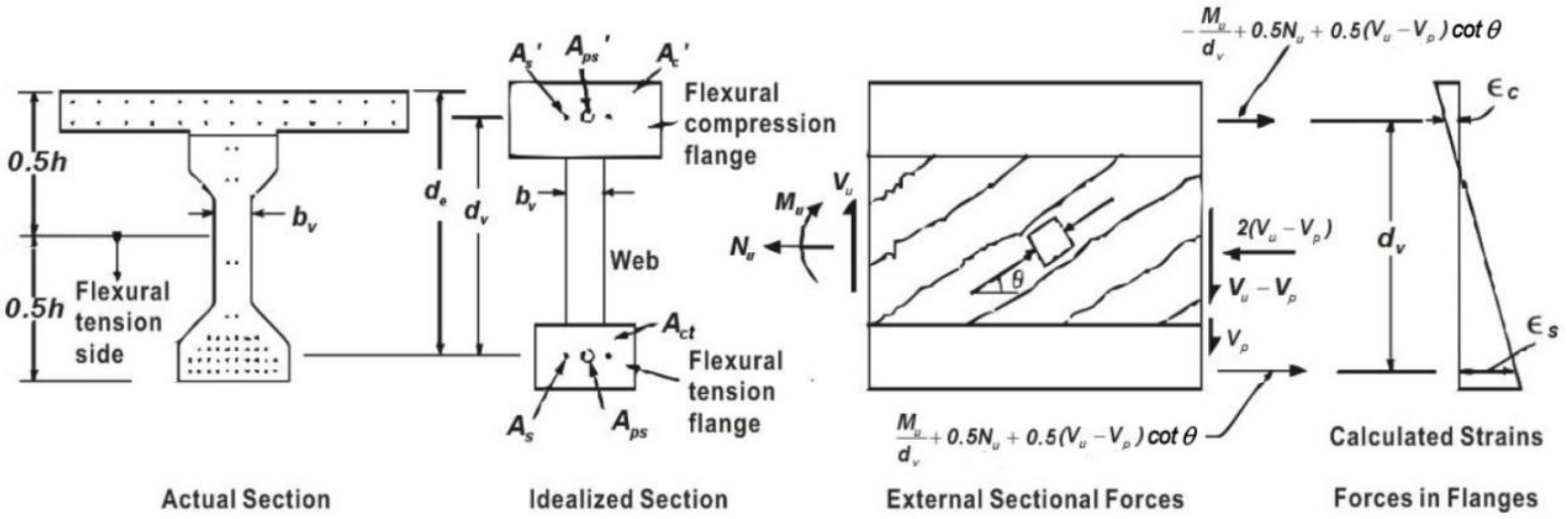

Figure CB5.2-3—More Accurate Calculation Procedure for Determining ε_x

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Concrete Shear History: ASD HB-9 1953/1965

- Simple stress based
- Constant concrete shear capacity not coupled with flexure and load-independent
- No direct consideration of shear inducing tension in flexural reinforcement
- Simple, constant shear reinforcement capacity

(2) Shear

Beams without web reinforcement:	
Longitudinal bars not anchored or plain concrete footings	$0.02\ f'_c$ (max. 75 psi.)
Longitudinal bars anchored . .	$0.03\ f'_c$ (max. 90 psi.)
Beams with web reinforcement . . .	$V=0.075\ f'_c bjd$
Horizontal shear in shear keys between slab and stem of T-beams and box girders	$0.15\ f'_c$

FORMULAS:

Shearing unit stress, as a measure of diagonal tension:

$$v=\frac{V}{bjd}$$

Stress in vertical web reinforcement:

$$f_v=\frac{V's}{A_v jd}$$

When a series of web bars or bent-up longitudinal bars are used, the web reinforcement shall be designed by the following formula:

$$A_v=\frac{V's}{f_v jd\ (\sin\ a+\cos\ a)}$$

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Concrete Shear History: LFD HB-12 1977

- Simple stress based
- Optional minimal coupling of shear capacity with flexure and loading
- No direct consideration of shear adding tension in flexural reinforcement
- Simple, constant shear reinforcement capacity

(B) Shear Stress Carried by Concrete

(1) For members subject to shear and flexure only, shear stress carried by concrete v_c shall not exceed $2\sqrt{f'_c}$ or $(.166\sqrt{f'_c})$ unless a more detailed calculation is made in accordance with (4).

(4) For members subject to shear and flexure only, v_c may be computed by

$$v_c = 1.9\sqrt{f'_c} + 2500\,\rho_w \frac{V_u d}{M_u} \qquad (6\text{-}22)$$

or $$\left(.158\sqrt{f'_c} + 17.2\rho_w\left(\frac{V_u d}{M_u}\right)\right)$$

(2) When shear reinforcement perpendicular to the axis of the member is used, the required area shall be computed by:

$$A_v = \frac{(v_u - v_c)b_w s}{f_y} \qquad (6\text{-}24)$$

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Concrete Shear History: LFD HB-17 2002 *(last published edition)*

- Chapter 8 Reinforced Concrete

8.16.6.2.1 Shear in Beams and One-Way Slabs and Footings

For members subject to shear and flexure only, V_c shall be computed by,

$$V_c = \left(1.9\sqrt{f'_c} + 2{,}500\,\rho_w \frac{V_u d}{M_u}\right) b_w d \qquad (8-48)$$

or,

$$V_c = 2\sqrt{f'_c}\, b_w d \qquad (8\text{-}49)$$

Note:

(a) V_c shall not exceed $3.5\sqrt{f'_c}\, b_w d$ when using more detailed calculations.

(b) The quantity $V_u d/M_u$ shall not be greater than 1.0 where M_u is the factored moment occurring simultaneously with V_u at the section being considered.

8.16.6.3.2 When shear reinforcement perpendicular to the axis of the member is used:

$$V_s = \frac{A_v f_y d}{s} \qquad (8-53)$$

- Chapter 9 Prestressed Concrete

9.20.2.1 The shear strength provided by concrete, V_c, shall be taken as the lesser of the values V_{ci} or V_{cw}.

9.20.2.2 The shear strength, V_{ci}, shall be computed by

$$V_{ci} = 0.6\sqrt{f'_c}\, b'd + V_d + \frac{V_i M_{cr}}{M_{max}} \qquad (9-27)$$

The moment causing flexural cracking at the section due to externally applied loads, M_{cr}, shall be computed by:

$$M_{cr} = \frac{I}{Y_t}\left(6\sqrt{f'_c} + f_{pe} - f_d\right) \qquad (9-28)$$

9.20.2.3 The shear strength, V_{cw}, shall be computed by

$$V_{CW} = \left(3.5\sqrt{f'_c} + 0.3\, f_{pc}\right) b'd + V_p \qquad (9-29)$$

9.20.3.1 The shear strength provided by web reinforcement shall be taken as:

$$V_s = \frac{A_v f_{sy} d}{s} \qquad (9-30)$$

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Concrete Shear History: LRFD 1994 1st Edition - Introduction of MCFT

- Unified approach for both nonprestressed & prestressed concrete
- Flexure & shear are coupled complicating load rating -- optional iterative process
- Concrete & shear reinforcement capacities variable based on loading & diagonal cracking angle
- New design consideration that shear adds tension in flexural reinforcement

Table 1. History of the American Association of Highway and Transportation Officials' (AASHTO's) adoption of the modified compression field theory for shear

Year	Notable Change to Concrete Shear Design	Specifications
1994	• Modified compression field theory is introduced. • Tables and iterations are needed for θ and β. • Strain ε_x is calculated at middepth or at maximum strain location in the web. • Minimum shear reinforcement increased about 50% over the AASHTO *Standard Specifications for Highway Bridges* (2002).	*AASHTO LRFD Bridge Design Specifications*, 1st ed.
2007	• An alternate method called the simplified method is introduced. It requires the evaluation of two nominal concrete shear resistances: the shear resistance when inclined cracking results from combined shear and moment V_{ci}, and the shear resistance when inclined cracking results from excessive principal tensions in the web V_{cw}. • Load and resistance factor design (LRFD) is required for all federally funded bridge designs.	Same method as LFD Chapter 9 Prestressed Concrete *AASHTO LRFD Bridge Design Specifications*, 4th ed.
2008	• Closed-form solution is provided (iteration is no longer needed). • Strain ε_s is calculated at tension reinforcement.	*AASHTO LRFD Bridge Design Specifications*, 4th ed. Interim Revisions
2010	• LRFD is required for all bridge designs.	
2017	• Alternate method (the simplified method) is removed.	*AASHTO LRFD Bridge Design Specifications*, 8th ed.

Source: Federal Highway Administration.

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Concrete Shear History: LRFD 2007 4th Edition – Simplified Formulas

$V_c = 0.0316\,\beta\sqrt{f'_c}\; b_v d_v$, if the procedures of Articles 5.8.3.4.1 or 5.8.3.4.2 are used (5.8.3.3-3)

V_c = the lesser of V_{ci} and V_{cw}, if the procedures of Article 5.8.3.4.3 are used

$$V_s = \frac{A_v f_y d_v (\cot\theta + \cot\alpha)\sin\alpha}{s} \quad (5.8.3.3\text{-}4)$$

$$V_{ci} = 0.02\sqrt{f'_c}b_v d_v + V_d + \frac{V_i M_{cre}}{M_{max}} \geq 0.06\sqrt{f'_c}b_v d_v \quad (5.8.3.4.3\text{-}1)$$

$$V_{cw} = \left(0.06\sqrt{f'_c} + 0.30 f_{pc}\right)b_v d_v + V_p \quad (5.8.3.4.3\text{-}3)$$

Simplified Formulas -- essentially same simplified equations as LFD Chapter 9 Prestressed Concrete but re-written for f'c in ksi units.

5.8.3.5 Longitudinal Reinforcement

$$A_{ps} f_{ps} + A_s f_y \geq \frac{|M_u|}{d_v \phi_f} + 0.5\frac{N_u}{\phi_c} + \left(\left|\frac{V_u}{\phi_v} - V_p\right| - 0.5V_s\right)\cot\theta \quad (5.8.3.5\text{-}1)$$

5.8.3.4.1 Simplified Procedure for Nonprestressed Sections

$\beta = 2.0$
$\theta = 45°$

Table 5.8.3.4.2-1 Values of θ and β for Sections with Transverse Reinforcement.

$\frac{v_u}{f'_c}$	$\varepsilon_x \times 1{,}000$								
	≤−0.20	≤−0.10	≤−0.05	≤0	≤0.125	≤0.25	≤0.50	≤0.75	≤1.00
≤0.075	22.3 6.32	20.4 4.75	21.0 4.10	21.8 3.75	24.3 3.24	26.6 2.94	30.5 2.59	33.7 2.38	36.4 2.23
≤0.100	18.1 3.79	20.4 3.38	21.4 3.24	22.5 3.14	24.9 2.91	27.1 2.75	30.8 2.50	34.0 2.32	36.7 2.18
≤0.125	19.9 3.18	21.9 2.99	22.8 2.94	23.7 2.87	25.9 2.74	27.9 2.62	31.4 2.42	34.4 2.26	37.0 2.13
≤0.150	21.6 2.88	23.3 2.79	24.2 2.78	25.0 2.72	26.9 2.60	28.8 2.52	32.1 2.36	34.9 2.21	37.3 2.08
≤0.175	23.2 2.73	24.7 2.66	25.5 2.65	26.2 2.60	28.0 2.52	29.7 2.44	32.7 2.28	35.2 2.14	36.8 1.96
≤0.200	24.7 2.63	26.1 2.59	26.7 2.52	27.4 2.51	29.0 2.43	30.6 2.37	32.8 2.14	34.5 1.94	36.1 1.79
≤0.225	26.1 2.53	27.3 2.45	27.9 2.42	28.5 2.40	30.0 2.34	30.8 2.14	32.3 1.86	34.0 1.73	35.7 1.64
≤0.250	27.5 2.39	28.6 2.39	29.1 2.33	29.7 2.33	30.6 2.12	31.3 1.93	32.8 1.70	34.3 1.58	35.8 1.50

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Concrete Shear History: LRFD 2008 4th Edition Interim Revisions

$$V_c = 0.0316\beta\lambda\sqrt{f'_c}\ b_v d_v \qquad (5.7.3.3\text{-}3)$$

$$V_s = \frac{A_v f_y d_v (\cot\theta + \cot\alpha)\sin\alpha}{s}\lambda_{duct} \qquad (5.7.3.3\text{-}4)$$

5.7.3.4.1—Simplified Procedure for Nonprestressed Sections

$\beta = 2.0$
$\theta = 45$ degrees

$$V_{ci} = 0.02\sqrt{f'_c}b_v d_v + V_d + \frac{V_i M_{cre}}{M_{max}} \geq 0.06\sqrt{f'_c}b_v d_v \qquad (5.8.3.4.3\text{-}1)$$

$$V_{cw} = \left(0.06\sqrt{f'_c} + 0.30 f_{pc}\right)b_v d_v + V_p \qquad (5.8.3.4.3\text{-}3)$$

Simplified formulas removed in 8th edition

Equations provided to directly compute β & θ from longitudinal strain, ε_s, at level of flexural reinforcement.

5.7.3.4.2—General Procedure

$$\beta = \frac{4.8}{(1+750\varepsilon_s)} \qquad (5.7.3.4.2\text{-}1)$$

$$\theta = 29 + 3500\varepsilon_s \qquad (5.7.3.4.2\text{-}3)$$

5.7.3.5—Longitudinal Reinforcement

$$A_{ps} f_{ps} + A_s f_y \geq \frac{|M_u|}{d_v \phi_f} + 0.5\frac{N_u}{\phi_c} + \left(\left|\frac{V_u}{\phi_v} - V_p\right| - 0.5V_s\right)\cot\theta \qquad (5.7.3.5\text{-}1)$$

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MCFT Methodology Background

- Analytical model for predicting load-deformation relationship in concrete in shear
- Fundamental publication:
  - Vecchio, Frank J., and Michael P. Collins. "The Modified Compression-Field Theory for Reinforced Concrete Elements Subjected to Shear." *ACI Journal* 83-22, March-April 1986: 219-231
  - Accessible online from the VecTor Analysis Group
    - https://www.vectoranalysisgroup.com/journal_publications/jp2.pdf

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MCFT Methodology Background

- Key assumptions
  - Membrane stress (In-Plane Shear and Axial Stress)
  - Uncracked concrete is capable of carrying tension; Cracked concrete is not

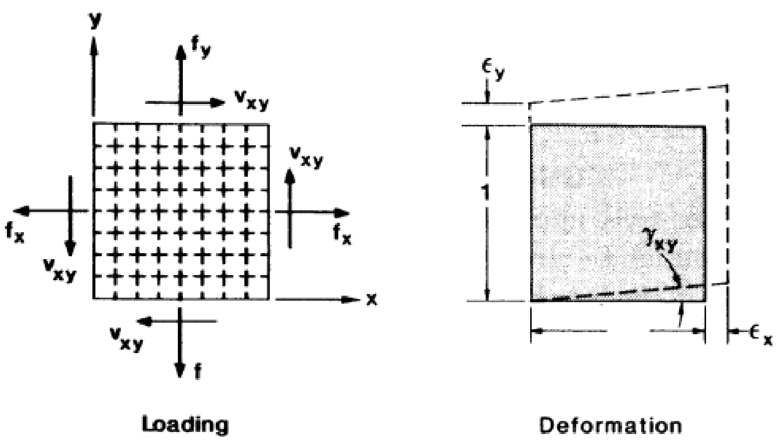
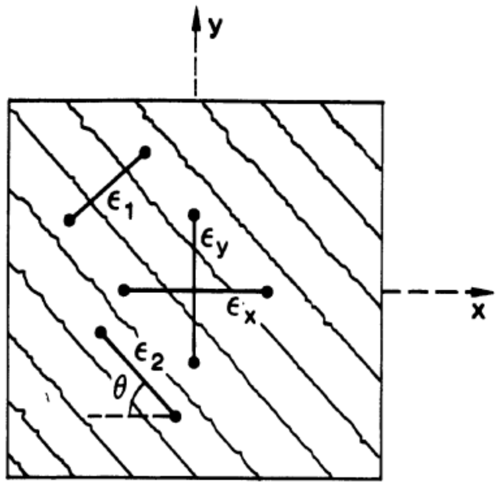


Fig. 2 — Membrane element



(a) Average Strains in Cracked Element

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MCFT Methodology Background

- Stress and strain in cracked, reinforced panels

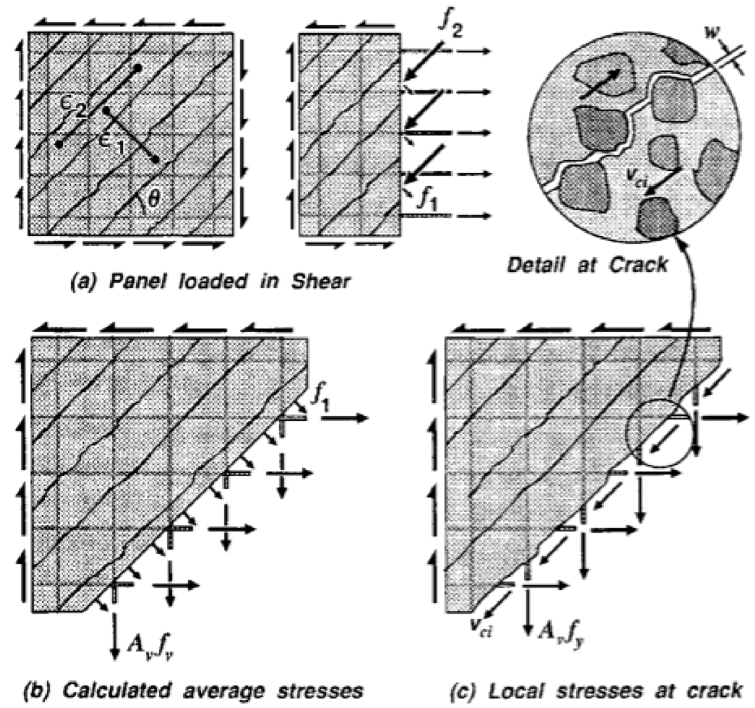

Fig. 4—Reinforced concrete panels subjected to shear

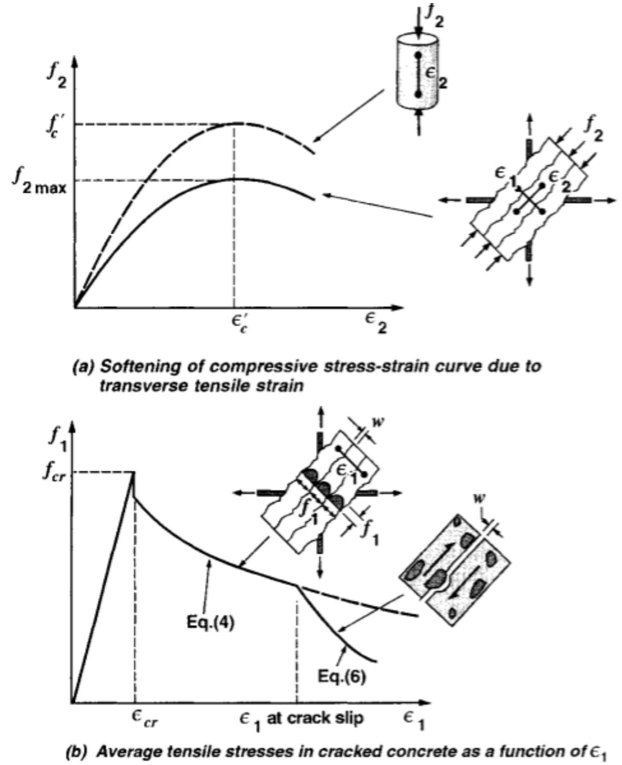

Fig. 5—Stress-strain relationships for cracked concrete

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MCFT Methodology Background

- Conclusions of the paper are summarized graphically

ϵ_1 = principal tensile strain in concrete (positive quantity)
ϵ_2 = principal compressive strain in concrete (negative quantity)

ϵ_x = strain in x-direction
ϵ_y = strain in y-direction

f_x = stress applied to element in x-direction
f_y = stress applied to element in y-direction

v_{xy} = shear stress on element relative to x, y axes

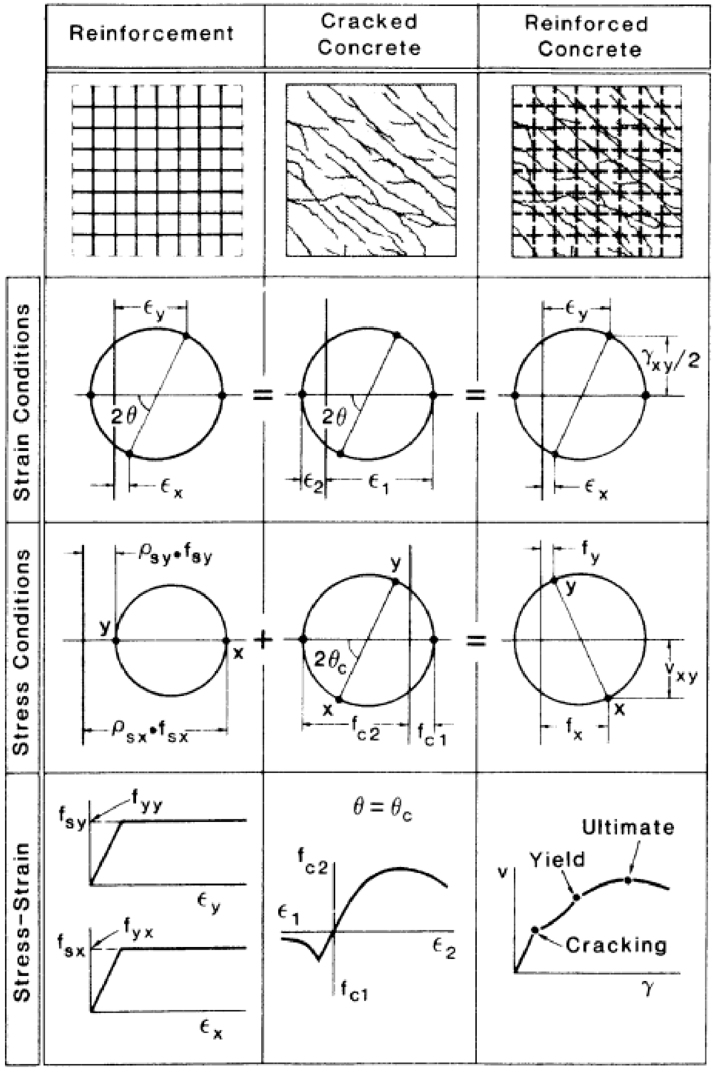

Fig. 20 — The modified compression-field theory for membrane elements

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MCFT Methodology Background

- Design Equations for Shear
- Fundamental publication:
  - Collins et al., A General Shear Design Method, ACI Structural Journal 93-S5, January-February 1996
  - Very similar to Appendix B5 in the current spec

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MCFT Methodology Background

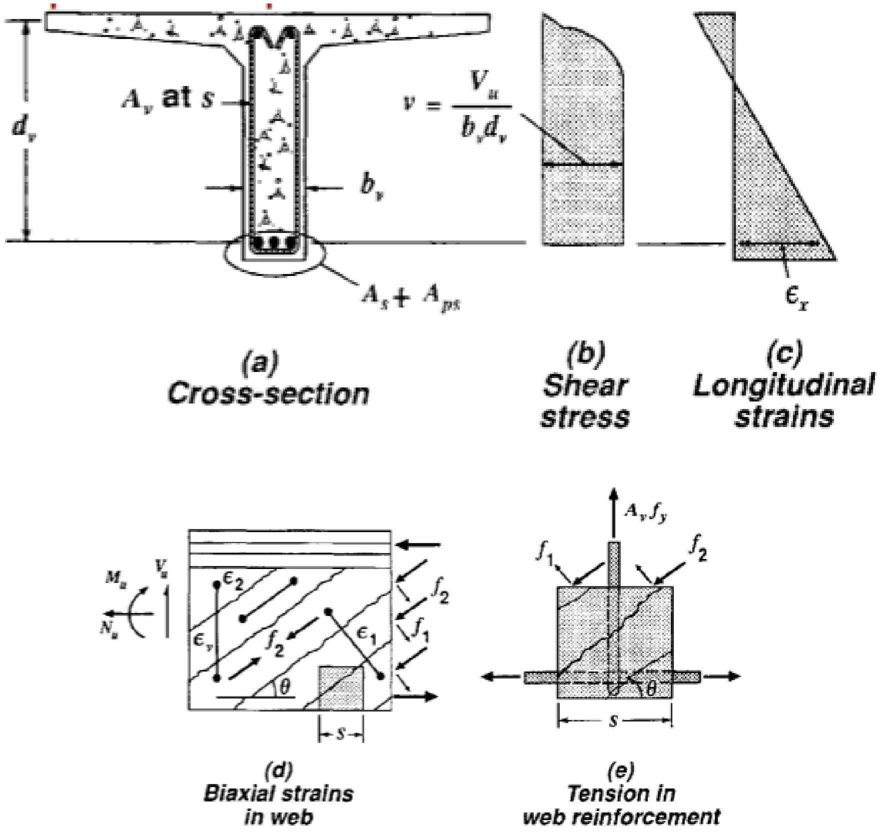

Fig. 6—Beam subjected to shear, moment, and axial load

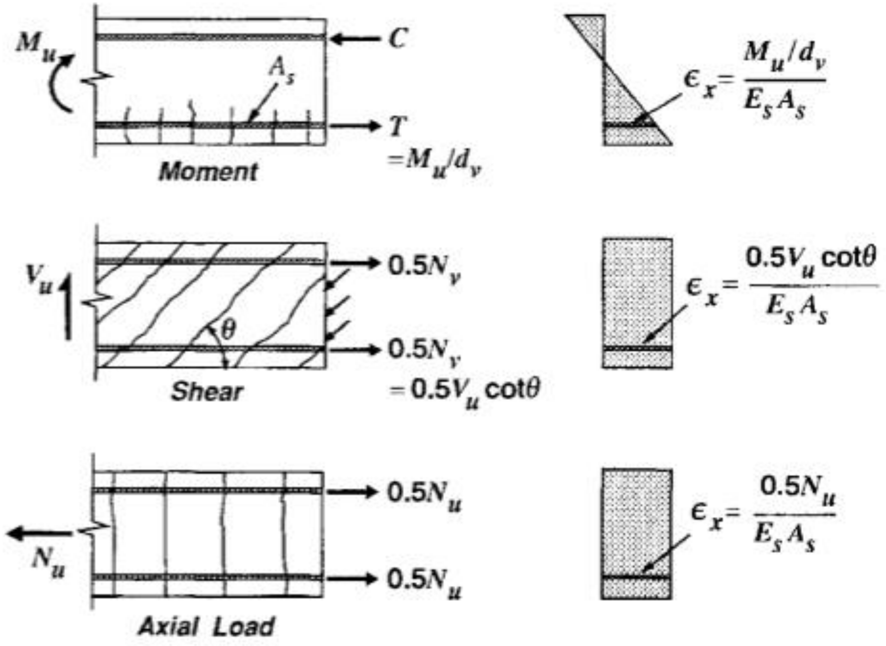

Fig. 7—Determination of strain ε_x for nonprestressed beam

$$\varepsilon_x = \frac{(M_u/d_v) + 0.5N_u + 0.5V_u \cot\theta - A_{ps} f_{po}}{E_s A_s + E_p A_{ps}} \geq 0 \qquad (7)$$

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MCFT Methodology Background

General Method
$V_n = V_c + V_s + V_p$
$V_c = \beta\sqrt{f'_c}\, b_v d_v$ $V_s = \dfrac{A_v f_y}{s} d_v \cot\theta$ where β and θ are functions of the strain, ϵ_x, shear stress, v, and crack spacing s_x where $v = \dfrac{V_n - V_p}{b_v d_v}$ and $\epsilon_x = \dfrac{M_u/d_v + 0.5(N_u + V_u\cot\theta) - A_{ps}f_{po}}{E_s A_s + E_p A_p}$

Strain at flexural tension steel level, not mid-height as in Appendix B5

Detailing Rules

Longitudinal steel must be detailed so that

$$A_s f_y + A_{ps} f_{ps} \geq \frac{M_u}{\phi d_v} + 0.5\frac{N_u}{\phi} + \left(\frac{V_u}{\phi} - 0.5V_s - V_p\right)\cot\theta$$

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MCFT Methodology Background

- θ and β combinations ensure:
  - Stirrups are near yield ($\varepsilon > 0.002$)
  - Principal stresses in concrete do not exceed crushing strength
  - The following relationship between average principal tensile strain in concrete and strain in steel reinforcement:

$$\varepsilon_1 = \varepsilon_x + \left[\varepsilon_x + 0.002\left(1 - \sqrt{1 - \frac{v}{f_c'}(\tan\theta + \cot\theta)\left(0.8 + 170\varepsilon_1\right)}\right)\right]\cot^2\theta \quad (13)$$

Table 1—Values of θ and β for members with web reinforcement

$\frac{v}{f_c'}$		Longitudinal strain $\varepsilon_x \times 1000$					
		≤ 0	≤ 0.25	≤ 0.50	≤ 1.00	≤ 1.50	≤ 2.00
≤ 0.050	θ deg	27.0	28.5	29.0	36.0	41.0	43.0
	β	4.88	3.49	2.51	2.23	1.95	1.72
≤ 0.075	θ deg	27.0	27.5	30.0	36.0	40.0	42.0
	β	4.88	3.01	2.47	2.16	1.90	1.65
≤ 0.100	θ deg	23.5	26.5	30.5	36.0	38.0	39.0
	β	3.26	2.54	2.41	2.09	1.72	1.45
≤ 0.150	θ deg	25.0	29.0	32.0	36.0	36.5	37.0
	β	2.55	2.45	2.28	1.93	1.50	1.24
≤ 0.200	θ deg	27.5	31.0	33.0	34.5	35.0	36.0
	β	2.45	2.33	2.10	1.58	1.21	1.00
≤ 0.250	θ deg	30.0	32.0	33.0	35.5	38.5	41.5
	β	2.30	2.01	1.64	1.40	1.30	1.25

Note: for β values in MPa units divide given values by 12.

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MCFT Methodology Background

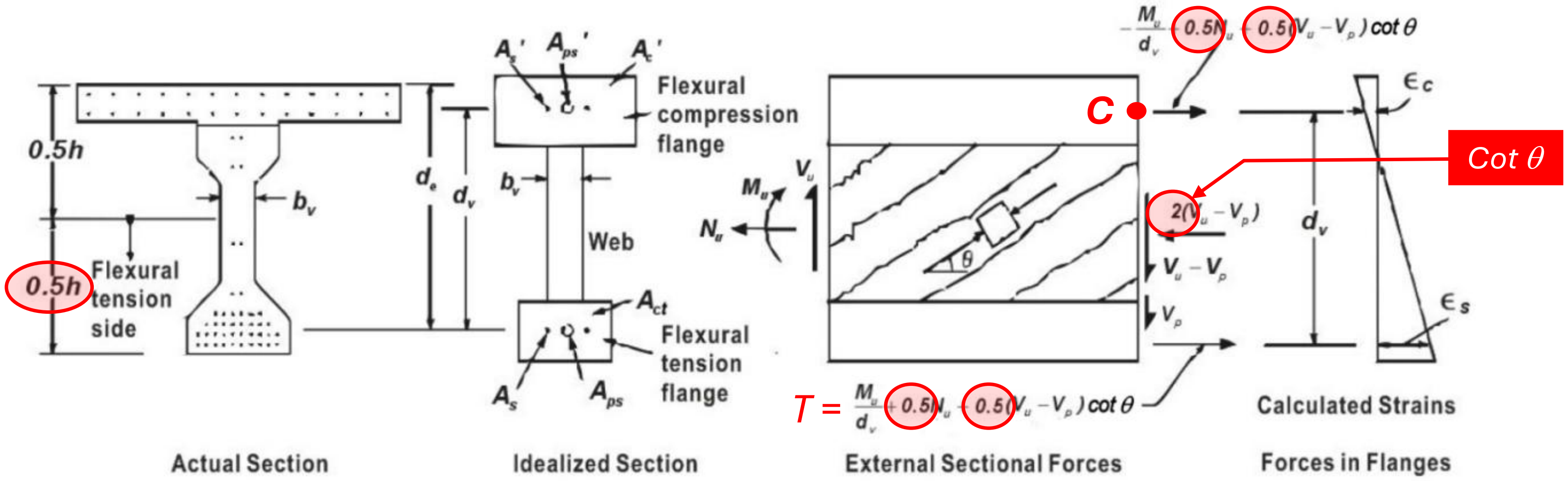

Figure CB5.2-3—More Accurate Calculation Procedure for Determining ε_x

$$\sum M_c = 0 = Mu + Nu\frac{d_v}{2} + (V_u - Vp)\cot(\theta)\frac{d_v}{2} - T\,d_v$$

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MCFT Methodology Background

- Assumed value of 26.6° for θ is reflected in current specification:

In Eqs. 5.7.3.4.2-1 through 5.7.3.4.2-3, ε_s is the net longitudinal tensile strain in the section at the centroid of the tension reinforcement as shown in Figures 5.7.3.4.2-1 and 5.7.3.4.2-2. In lieu of more involved procedures, ε_s may be determined by Eq. 5.7.3.4.2-4:

$$\varepsilon_s = \frac{\left(\frac{|M_u|}{d_v} + 0.5N_u + |V_u - V_p| - A_{ps}f_{po}\right)}{E_sA_s + E_pA_{ps}} \qquad (5.7.3.4.2\text{-}4)$$

MCFT for BrDR Users

MCFT Methodology Background

- REFERENCES:
    - Vecchio, Frank J. and Michael P. Collins. “The Modified Compression-Field Theory for Reinforced Concrete Elements Subjected to Shear”. *ACI Journal* 83-22, March-April 1986: 219-231.
    - Collins, Michael P., Denis Mitchell, Perry Adebar, and Frank J. Vecchio. “A General Shear Design Method”, *ACI Structural Journal* 93-S5, January-February 1996: 36-45.

MCFT Issues in BrDR

AASHTOWare Bridge Analysis TAG MCFT-related Issues

- BSSD-3560 Longitudinal reinforcement check $A_{ps}f_{ps} < A_s f_y$
- BSSD-4053 Low shear capacity when A_{ps} not on flexural tension side of beam cross-section
- BSSD-4782 Applicability of Minimum M_u limit for load ratings
- BSSD-5167 Non-convergence of iterative shear capacity when M_U changes sign
- BSSD-5725 Effect of strand development on A_{ps} when computing longitudinal strain, ε_S
- BSSD-5758 Assuming longitudinal strain = 0 when $M_u < M_{cr}$ -- differences between Art. 5.7.3.4.2 & Appendix B5.2

MCFT Issues in BrDR

AASHTOWare Bridge Analysis TAG MCFT-related Issues

- AASHTOWare Bridge Task Force Chair, **Jen Hart**, along with Analysis TAG co-chairs, **Yihong Gao** & **Robby Tennant**, have reached out to AASHTO Safety & Evaluation and Concrete Technical Subcommittees seeking clarification of LRFD design specification and MBE provisions
- AASHTO technical committee chairs have facilitated TEAMS meetings with Concrete Subject Matter Experts
- Two meetings held this year with two additional meetings planned
- Goal is possible preparation of AASHTO ballot items for next year

MCFT Issues in BrDR

- BSSD-3560 Longitudinal reinforcement check $A_{ps}f_{ps} < A_sf_y$

5.7.3.5—Longitudinal Reinforcement

Where consideration of torsion is required these provisions shall be amended as specified in Article 5.7.3.6.3.

Except as specified herein, at each section the

development shall be accounted for.

For pretensioned sections, including those with debonded strands, the tensile force in the prestressing reinforcement, $A_{ps}f_{ps}$, shall exceed the tensile forces of the nonprestressed reinforcement, A_sf_y, at all sections. Development of straight and bent-up strands as well as overhangs, if present, shall be considered for determining the value of $A_{ps}f_{ps}$ and A_sf_y.

Except as may be required by Article 5.7.3.6.3,

C5.7.3.5

Shear causes tension in the longitudinal reinforcement. For a given shear, this tension becomes larger as θ becomes smaller and as V_c becomes larger.

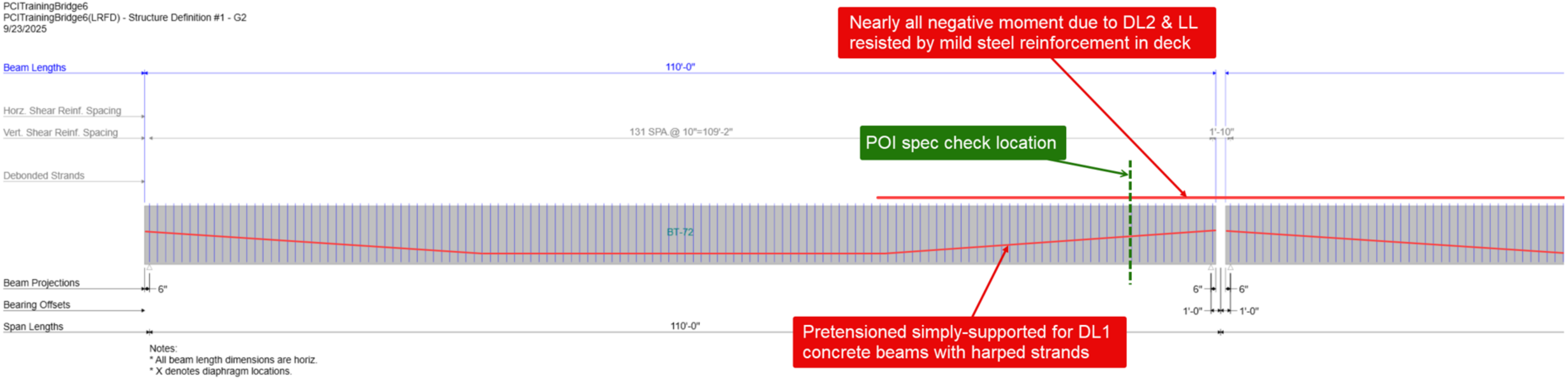
The tension in the longitudinal reinforcement

NO EXPLANATORY OR QUALIFYING COMMENTARY

At maximum moment locations, the shear force

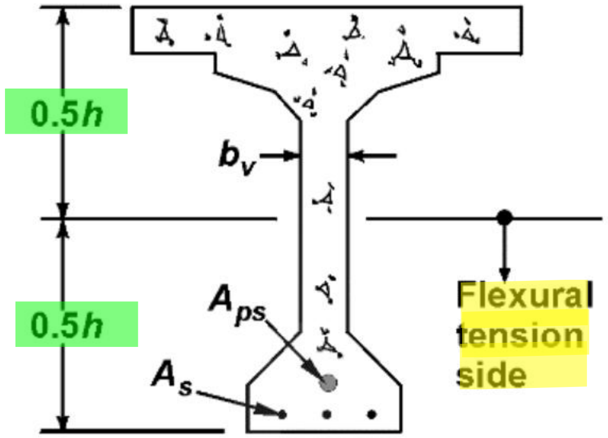
MCFT Issues in BrDR

- BSSD-3560 *(continued)*



MCFT Issues in BrDR

- BSSD-4053 Low shear capacity when A_{ps} not on flexural tension side of beam cross-section
  - Specification stipulates reinforcement being located on '**flexural tension side**'
  - For post-tensioned members, A_{ps} is typically defined as a total force located at along a c.g. profile
  - Implementation becomes problematic in moment reversal zones
  - Significant shear capacity reduction when A_{ps} = 0 (essentially RC member)



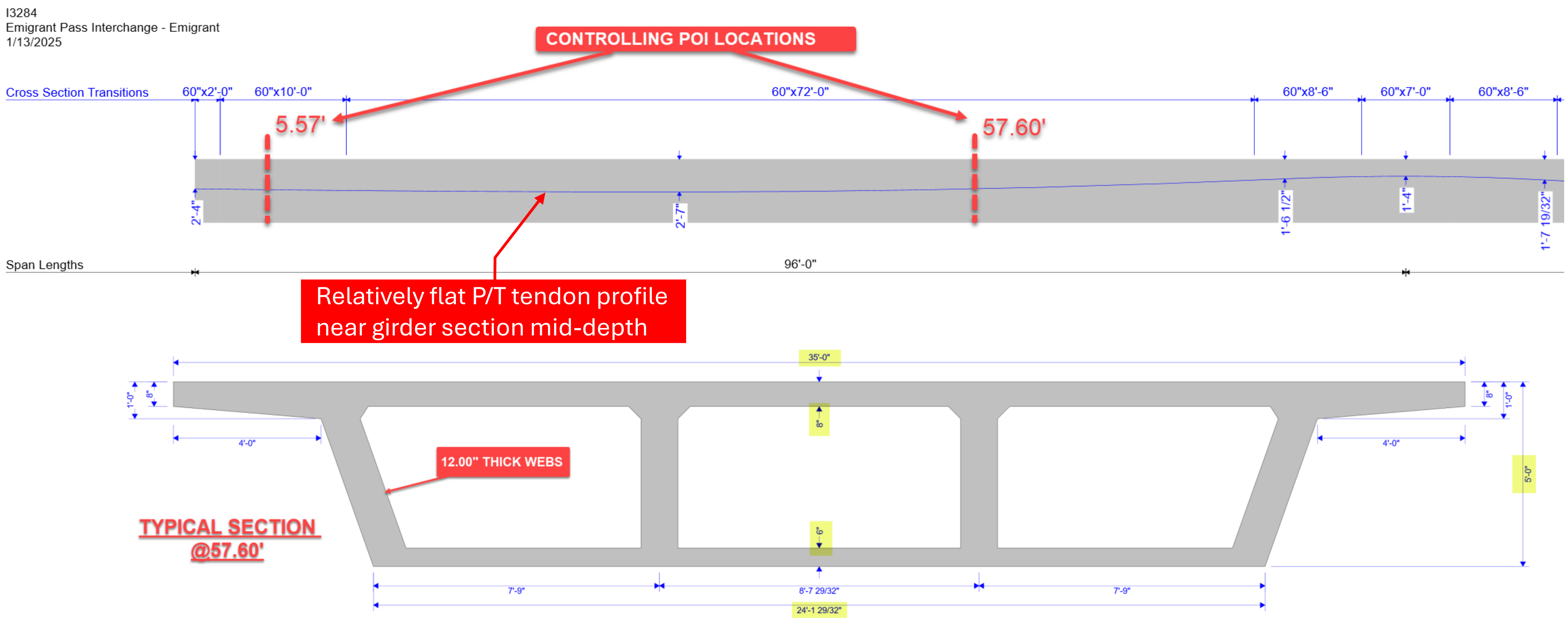
$$\beta = \frac{4.8}{(1+750\varepsilon_s)} \qquad (5.7.3.4.2\text{-}1)$$

$$\theta = 29 + 3500\varepsilon_s \qquad (5.7.3.4.2\text{-}3)$$

$$\varepsilon_s = \frac{\left(\frac{|M_u|}{d_v} + 0.5N_u + |V_u - V_p| - A_{ps}f_{po}\right)}{E_s A_s + E_p A_{ps}} \qquad (5.7.3.4.2\text{-}4)$$

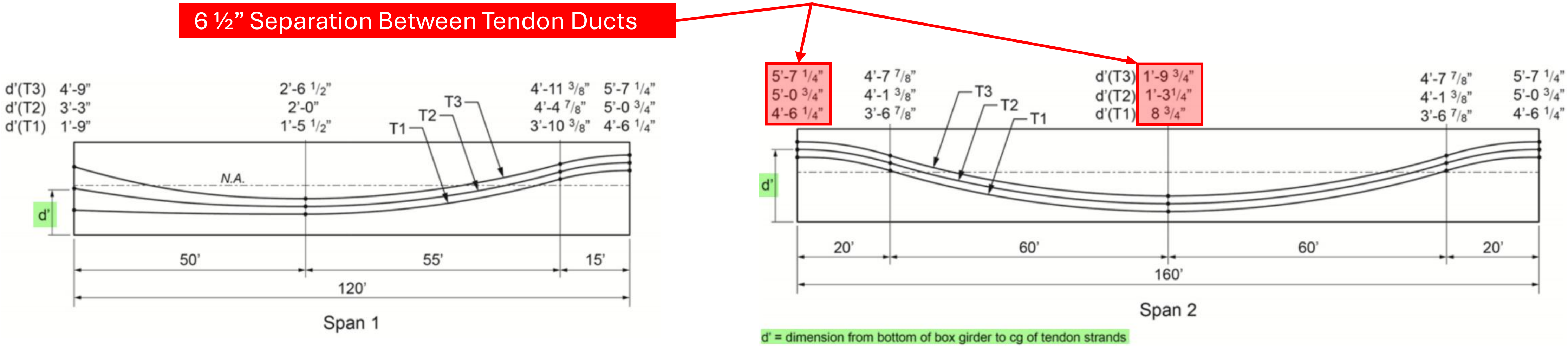
MCFT Issues in BrDR

- BSSD-4053 *(continued)*



MCFT Issues in BrDR

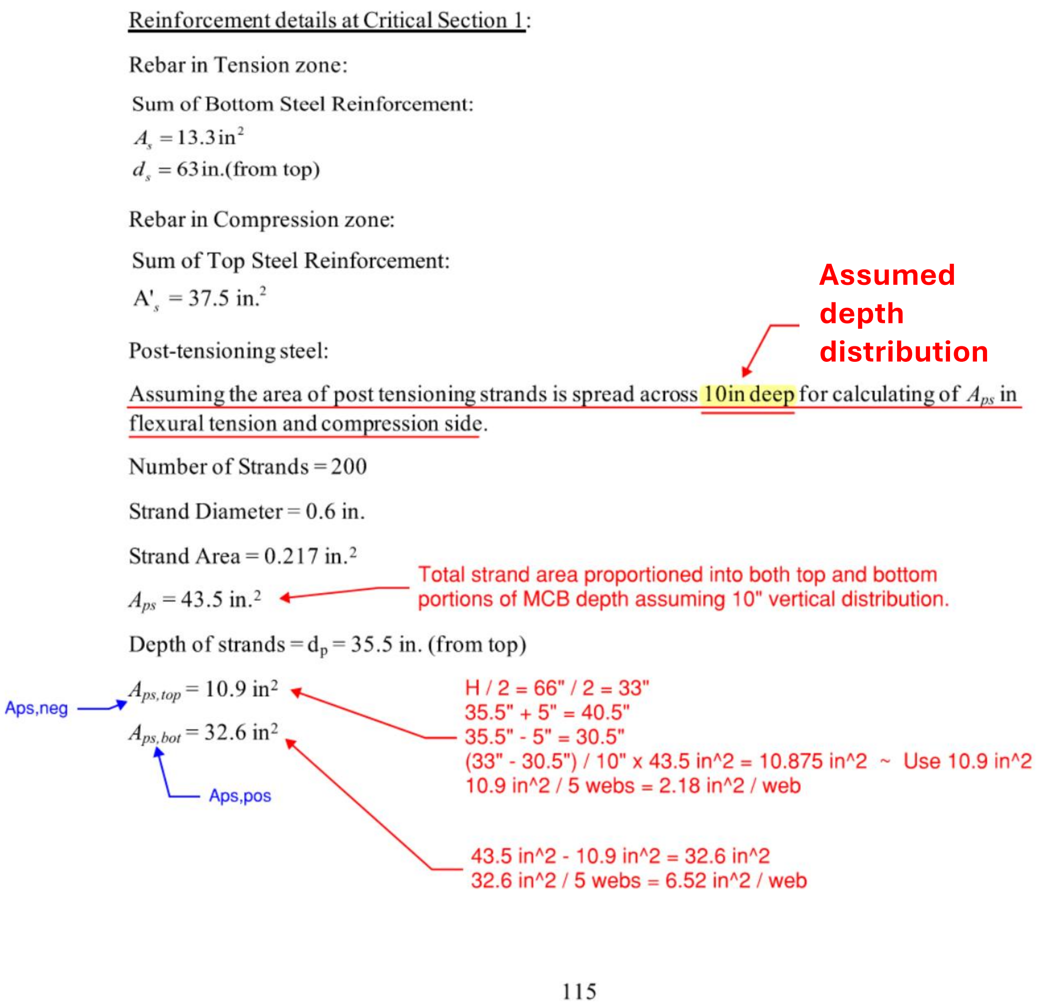
- BSSD-4053 *(continued)*
  - Prestress force is known to be vertically distributed and not applied at a single height location, but exact location of individual tendon paths may not be known



Post-Tensioned Box Girder Design Manual June 2016

MCFT Issues in BrDR

- BSSD-4053 *(continued)*
  - Excerpt from FHWA Pub FHWA-HIF-22-025 *Concrete Bridge Shear Load Rating Guide & Examples: Using Modified Compression Field Theory*
  - 10” vertical height distribution depth assumed for A_{ps}
  - **Spec guidance for distribution height of A_{ps} would be beneficial**



Reinforcement details at Critical Section 1:

Rebar in Tension zone:

Sum of Bottom Steel Reinforcement:

$A_s = 13.3\,\text{in}^2$

$d_s = 63\,\text{in.(from top)}$

Rebar in Compression zone:

Sum of Top Steel Reinforcement:

$A'_s = 37.5\ \text{in.}^2$

Post-tensioning steel:

Assuming the area of post tensioning strands is spread across 10in deep for calculating of A_{ps} in flexural tension and compression side.

Number of Strands = 200

Strand Diameter = 0.6 in.

Strand Area = 0.217 in.^{2}

$A_{ps} = 43.5\ \text{in.}^2$

Depth of strands = d_p = 35.5 in. (from top)

$A_{ps,top} = 10.9\ \text{in}^2$

$A_{ps,bot} = 32.6\ \text{in}^2$

115

MCFT Issues in BrDR

- BSSD-4053 *(continued)*

ALTERNATIVE SOLUTION

- AASHTO LRFD specs recognizes issue
- Verbiage included in Article CB5.2:

"In some situations, it will be more appropriate to determine ε_x using the more accurate procedure of Eq. CB5.2-1 rather than the simpler Eqs. B5.2-3 through B5.2-5"

- Consideration being given to add 'Moment Curvature' (moment-shear strength interaction) in BrDR based on explicitly computed mid-depth strain, ε_x

SECTION 5: CONCRETE STRUCTURES 5-295

APPENDIX B5—GENERAL PROCEDURE FOR SHEAR DESIGN WITH TABLES

B5.1—BACKGROUND

The general procedure herein is an acceptable alternative to the procedure specified in Article 5.7.3.4.2. The procedure in this Appendix utilizes tabularized values of β and θ instead of Eqs. 5.7.3.4.2-1, 5.7.3.4.2-2, and 5.7.3.4.2-3. Appendix B5 is a complete presentation of the general procedures in the AASHTO *LRFD Bridge Design Specifications* (2007) without any interim changes.

B5.2—SECTIONAL DESIGN MODEL—GENERAL PROCEDURE

CB5.2

For members containing at least the minimum amount of transverse reinforcement, ε_x can be taken as:

$$\varepsilon_x = \frac{\varepsilon_t + \varepsilon_c}{2} \quad \text{(CB5.2-1)}$$

where ε_t and ε_c are positive for tensile strains and negative for compressive strains.

In some situations, it will be more appropriate to determine ε_x using the more accurate procedure of Eq. CB5.2-1 rather than the simpler Eqs. B5.2-3 through B5.2-5. For example, the shear capacity of sections near the ends of precast, pretensioned simple beams made continuous for live load will be estimated in a very conservative manner by Eqs. B5.2-3 through B5.2-5 because, at these locations, the prestressing strands are located on the flexural compression side and, therefore, will not be included in A_{ps}. This will result in the benefits of prestressing not being accounted for by Eqs. B5.2-3 through B5.2-5.

MCFT Issues in BrDR

- BSSD-4782 Applicability of Minimum M_u limit for load ratings

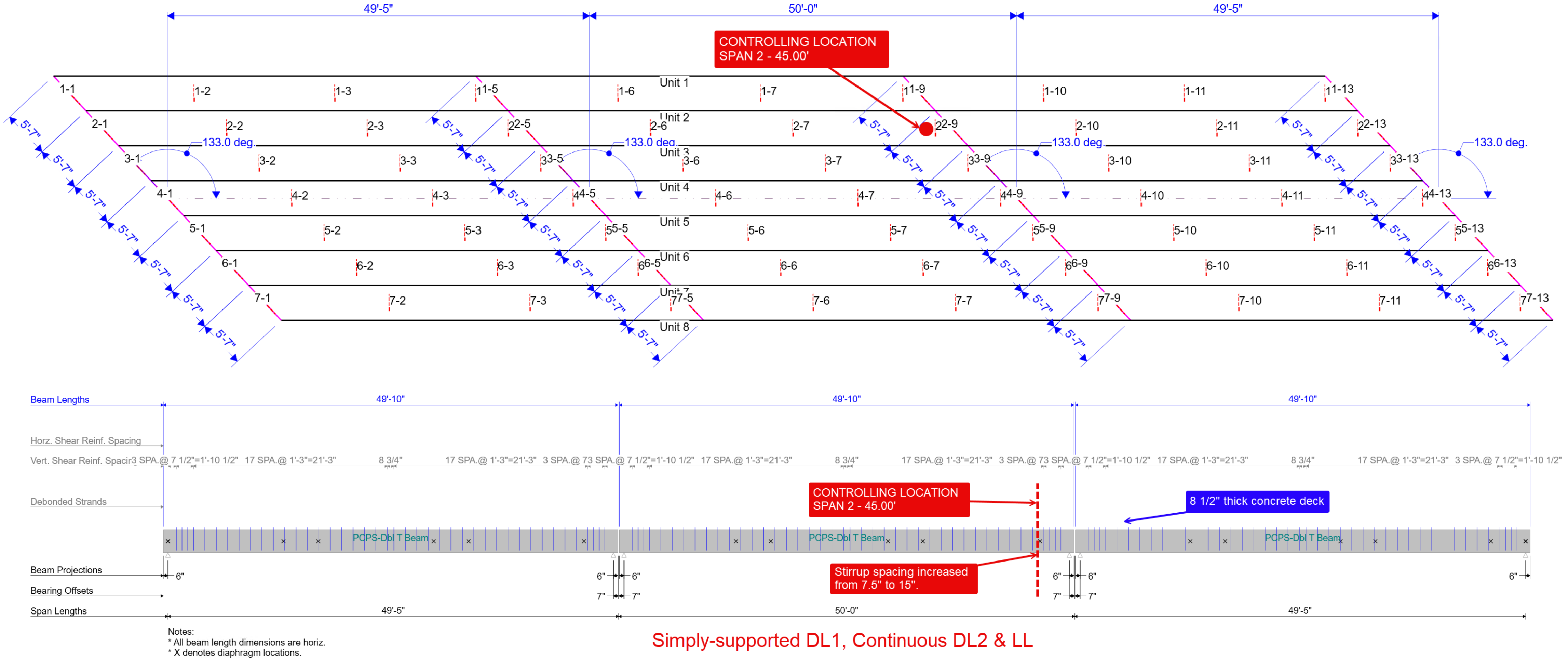
$$\varepsilon_s = \frac{\left(\dfrac{|M_u|}{d_v} + 0.5N_u + |V_u - V_p| - A_{ps} f_{po}\right)}{E_s A_s + E_p A_{ps}} \qquad (5.7.3.4.2\text{-}4)$$

where:

$|M_u|$ = absolute value of the factored moment at the section, not taken less than $|V_u - V_p| d_v$ (kip-in.)

MCFT Issues in BrDR

- BSSD-4782 *(continued)*



Simply-supported DL1, Continuous DL2 & LL

MCFT Issues in BrDR

- BSSD-4782 *(continued)*

Spec Check Detail for 6A.4.2.1 Shear-5.7.3.4 Procedures for Determining Shear Resistance

```
6A.4.2.1 Shear - 5 Concrete Structures
6A.4.2.1 Shear - 5.7 Shear and Torsion
6A.4.2.1 Shear - 5.7.3 Sectional Design Model
6A.4.2.1 Shear - 5.7.3.4 Procedures for Determining Shear Resistance
(AASHTO Manual for Bridge Evaluation, Third Edition with 2024 Interims)

PS Tee - At Location = 94.4167 (ft) - Left      Stage 3

Calculation of Beta/Theta
-------------------------

---(Appendix B Option)-----
      Es = 29000.004 (kips/in^2)
     phi = 0.900
     f'c = 4.500 (kips/in^2)
      fy = 40.000 (kips/in^2)
Agg diam = 1.000 (in)
      Vp = -20.736 (kips)
      Ep = 25000.000 (kips/in^2)
 As(pos) = 0.000 (in^2)  (used for Positive Mu)
 As(neg) = 4.400 (in^2)  (used for Negative Mu)
Aps(pos) = 2.740 (in^2)  (used for Positive Mu)
Aps(neg) = 0.000 (in^2)  (used for Negative Mu)
     fpo = 105.000 (kips/in^2)
      Ec = 3865.202 (kips/in^2)
```

Mild steel reinforcement in deck for -Mu

No prestress strand area for -Mu

Concurrent forces

LRFD Eq. 5.7.3.4.2-4 / B5.2-4 "Minimum Mu" provision = |Vu - Vp| x dv = -215.7 k-ft

(85% of -Mu,max @ interior support)
80X larger than computed **concurrent** Mu

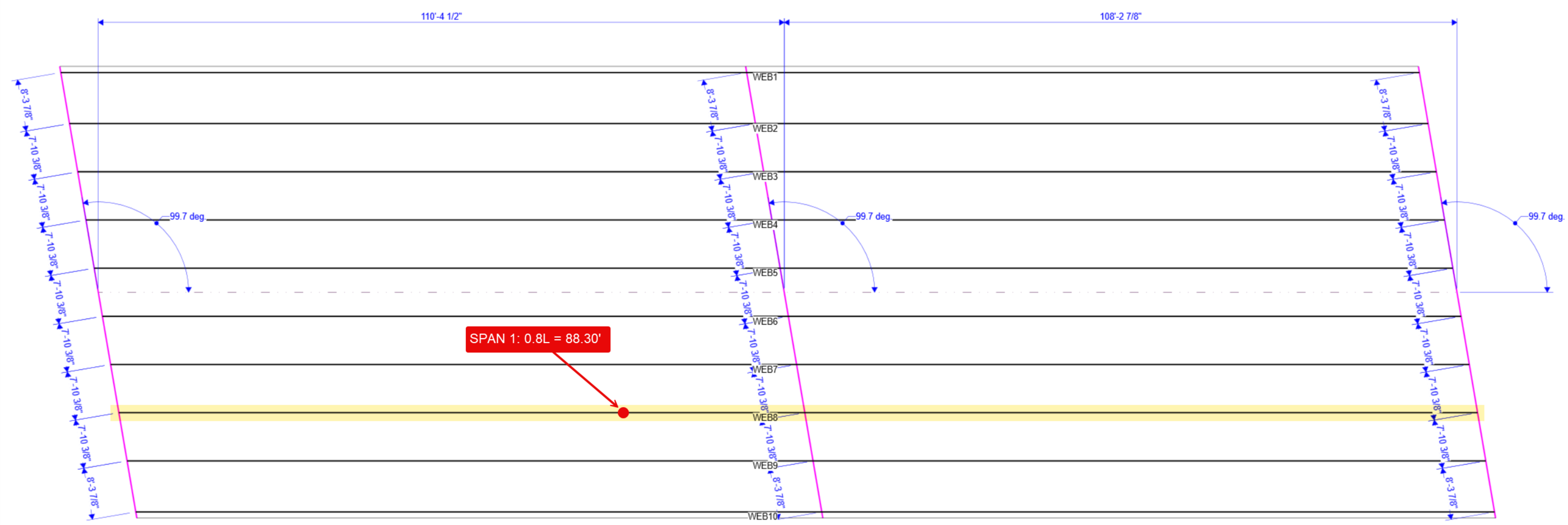
Limit State	Load Comb	Epsilon	Theta	Beta	Governing Action	Mu (kip-in)	Mu Calc (kip-in)	Vu (kips)	Nu (kips)	bv (in)	dv (in)	Sx (in)	Sxe (in)	Act (in^2)	Av (in^2)	As (in^2)
STR-II	1, PermitS~	-0.000048	32.23	4.79	Max M	2443.33	2443.33	-85.63	0.00	18.00	27.72	27.72	23.47	384.00	0.41	0.00
STR-II	1, PermitS~	0.000583	46.31	2.17	Min M	-1108.19	1558.64	-71.11	0.00	18.00	30.94	30.94	26.19	862.73	0.40	4.40
STR-II	1, PermitS~	-0.000064	32.21	4.81	Max V	2365.26	2365.26	-27.21	0.00	18.00	27.72	27.72	23.47	384.00	0.41	0.00
STR-II	1, PermitS~	0.000930	50.04	1.76	Min V	-32.16	2587.60	-104.37	0.00	18.00	30.94	30.94	26.19	862.73	0.40	4.40
SER-I	1, PermitS~	-0.000057	32.21	4.81	Max M	2005.12	2005.12	-70.00	0.00	18.00	27.72	27.72	23.47	384.00	0.41	0.00

```
Load Combination Legend:

 Code     Vehicle
-------------------------
    1    CA P 7 Split - Permit Truck + Lane
```

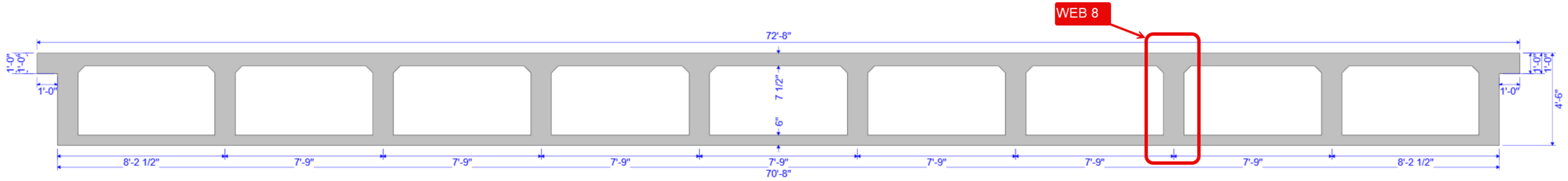
MCFT Issues in BrDR

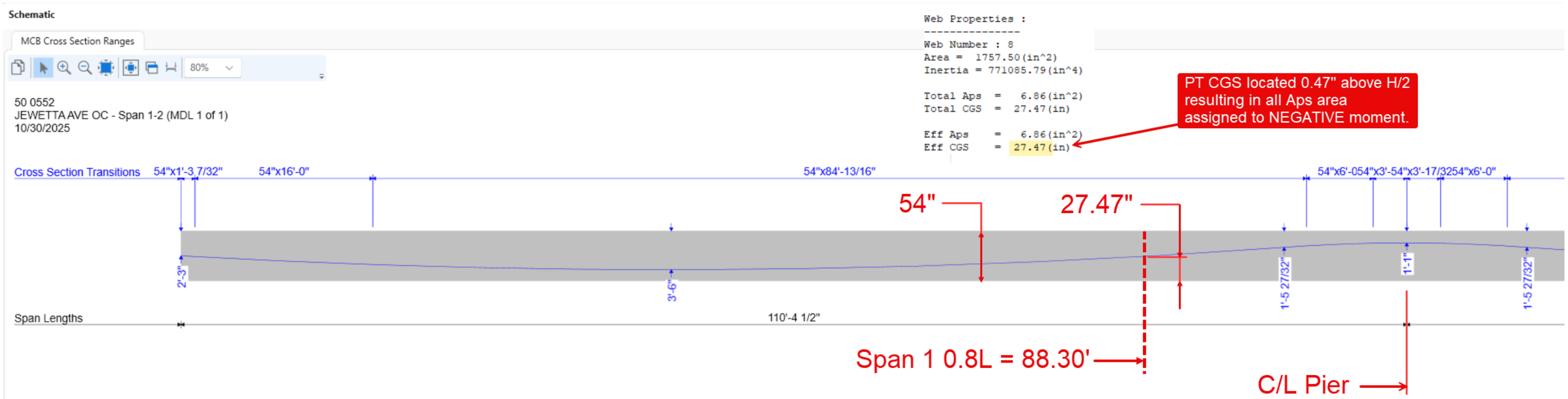
- BSSD-5167 Non-convergence of iterative shear capacity when M_U changes sign
    - Contraflexure region



MCFT Issues in BrDR

- BSSD-5167 *(continued)*





WJE / ProMiles

MCFT Issues in BrDR

- BSSD-5167 *(continued)*
  - Very different load ratings for essentially the same live load

Spec Check Detail for 6A.4.2.1 General Load Rating Equation - Concrete Shear

```
6A Load and Resistance Factor Rating
6A.4 Load Rating Procedures
6A.4.2 General Load-Rating Equation
6A.4.2.1 Concrete Shear General
(AASHTO Manual for Bridge Evaluation, Third Edition with 2024 Interims)

PT MultiCellBox Web 8 - At Location = 88.3040 (ft) - Left     Stage 3

Shear Rating Factor Calculations

Input:

Condition Factor      =     1.0000
System Factor         =     1.0000

DC Shear (Max)        =  -100.7014 (kip)
DC Shear (Min)        =  -100.7014 (kip)
DW Shear (Max)        =    -1.6585 (kip)
DW Shear (Min)        =    -1.6585 (kip)
DW-WS Shear (Max)     =     0.0000 (kip)
DW-WS Shear (Min)     =     0.0000 (kip)
Secondary PT Shear (Max) =    7.8909 (kip)
Secondary PT Shear (Min) =    7.8909 (kip)
```

Very different load ratings for essentially the same live load.

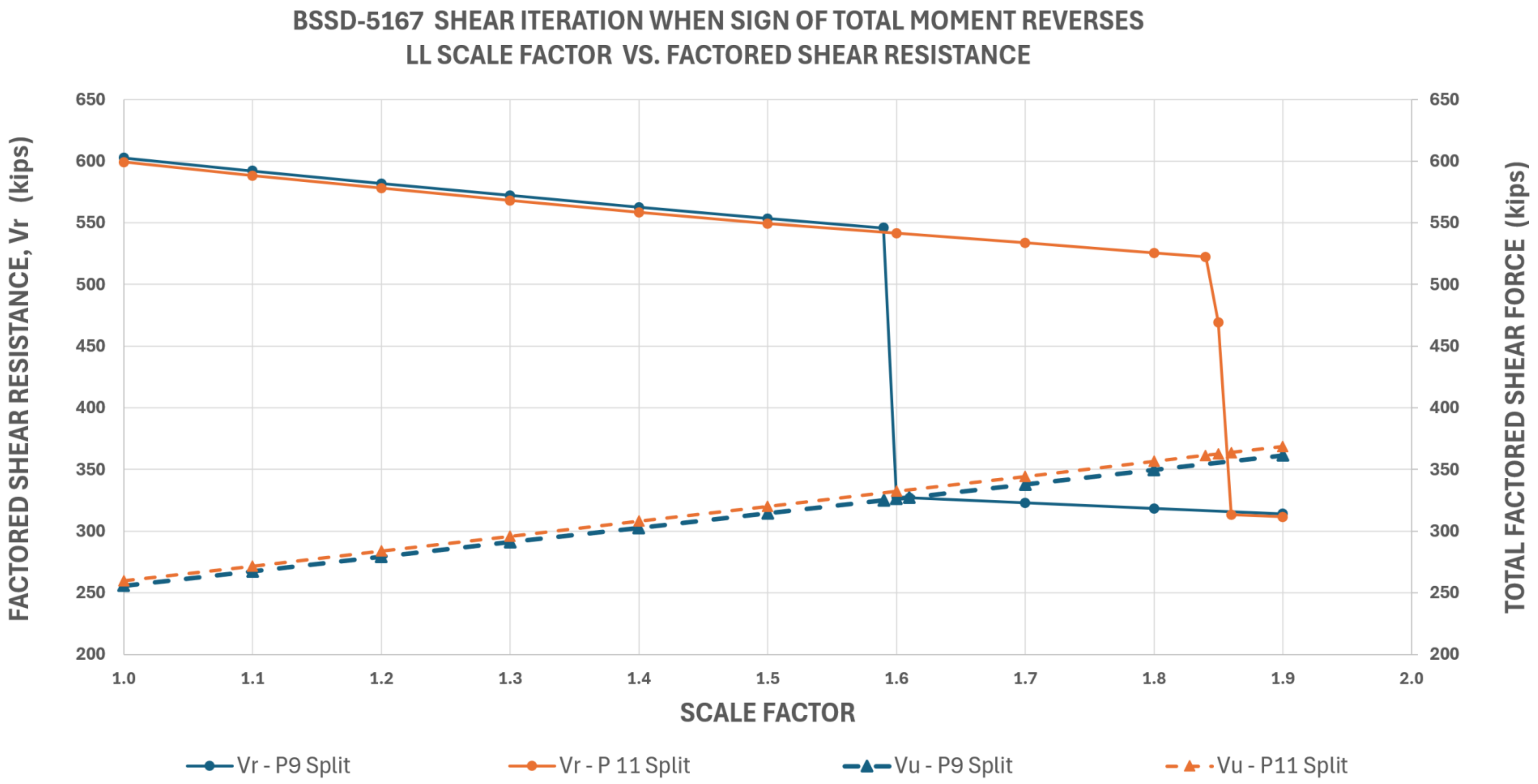
Load	Load Combo	Limit State	Governing Action	LL (kip)	Adj. LL (kip)	Load Factors DC	DW	DW-WS	PT	LL	Phi	Vn (kip)	-- Override -- Phi	Vn (kip)	RF	Capacity (Ton)
PermitSpec	1	STR-II	Max M	-58.50	1.48	1.25	1.50	1.50	1.00	1.20	0.90	-363.43	---	---	2.958	357.87
PermitSpec	1	STR-II	Min M	-10.11	-25.54	1.25	1.50	1.50	1.00	1.20	0.90	-362.42	---	---	15.487	1873.94
PermitSpec	1	STR-II	Max V	3.33	1.48	1.25	1.50	1.50	1.00	1.20	0.90	506.35	---	---	99.000	11979.00
PermitSpec	1	STR-II	Min V	-97.80	-25.54	1.25	1.50	1.50	1.00	1.20	0.90	-363.42	---	---	1.608	194.59
PermitSpec	2	STR-II	Max M	-58.50	1.48	1.25	1.50	1.50	1.00	1.20	0.90	-363.43	---	---	2.958	437.73
PermitSpec	2	STR-II	Min M	-10.68	-25.54	1.25	1.50	1.50	1.00	1.20	0.90	-650.66	---	---	34.897	5164.71
PermitSpec	2	STR-II	Max V	3.33	1.48	1.25	1.50	1.50	1.00	1.20	0.90	506.35	---	---	99.000	14652.00
PermitSpec	2	STR-II	Min V	-100.99	-25.54	1.25	1.50	1.50	1.00	1.20	0.90	-650.66	---	---	3.691	546.21

Load Combination Legend:

Code	Vehicle	
1	P 9 Split	(LRFR -54kips) - Permit Truck + Lane
2	P11 Split	(LRFR -54kips) - Permit Truck + Lane

MCFT Issues in BrDR

- BSSD-5167 *(continued)*



MCFT Issues in BrDR

- BSSD-5725 Effect of strand development on A_{ps} when computing longitudinal strain, ε_s

- Article 5.7.3.4.2 states in calculating A_{ps},the area of tendons terminated less than their development length from the section under consideration should be reduced **in proportion to lack of <u>full development</u>**.
- Various reference publications take different approaches – full strand development length vs transfer length *(PCI Bridge Design Manual; MnDOT & IDOT Design Manuals; FHWA Concrete Bridge Shear Load Rating Guide & Examples)*

5.7.3.4.2—General Procedure

The parameters β and θ may be determined either by the provisions herein, or alternatively by the provisions of Appendix B5.

For sections containing at least the minimum amount of transverse reinforcement specified in Article 5.7.2.5, the value of β may be determined by Eq. 5.7.3.4.2-1:

$$\varepsilon_s = \frac{\left(\frac{|M_u|}{d_v} + 0.5N_u + |V_u - V_p| - \boxed{A_{ps}} f_{po}\right)}{E_s A_s + E_p \boxed{A_{ps}}} \quad (5.7.3.4.2\text{-}4)$$

Within the transfer length, f_{po} shall be increased linearly from zero at the location where the bond between the strands and concrete commences to its full value at the end of the transfer length.

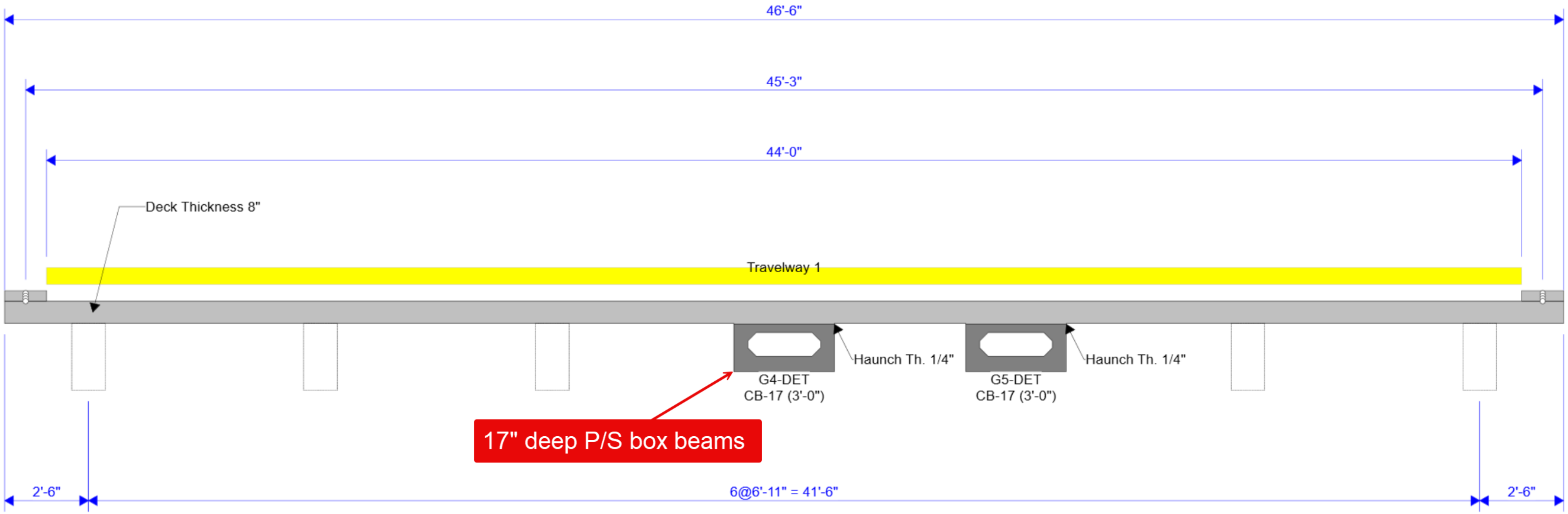
The flexural tension side of the member shall be taken as the half-depth containing the flexural tension zone, as illustrated in Figure 5.7.3.4.2-1.

In the use of Eqs. 5.7.3.4.2-1 through 5.7.3.4.2-4, the following should be considered:

- $|M_u|$ should not be taken less than $|V_u - V_p|d_v$.
- In calculating A_s and A_{ps} the area of bars or tendons terminated less than their development length from the section under consideration should be reduced in proportion to their lack of full development.
- If the value of ε_s calculated from Eq. 5.7.3.4.2-4 is negative, it should be taken as zero or the value

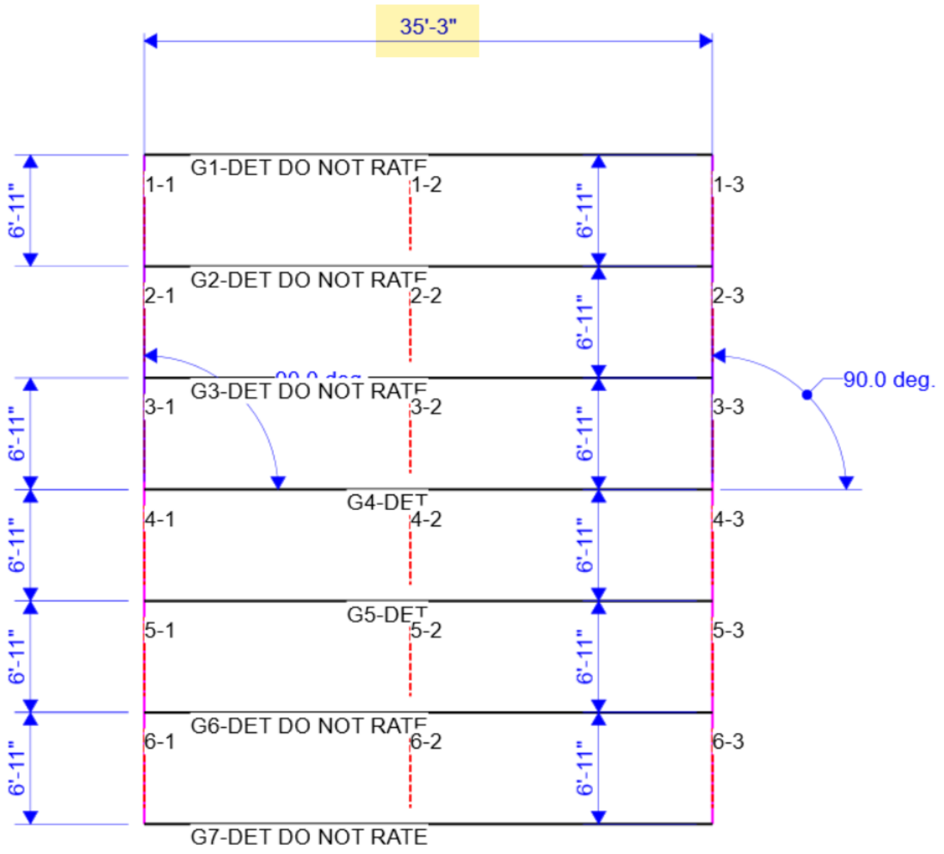
MCFT Issues in BrDR

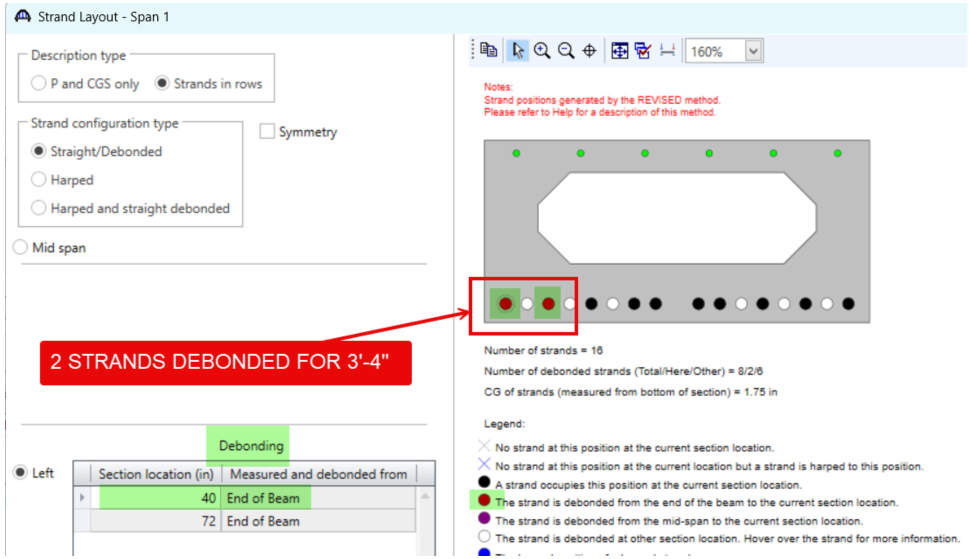
- BSSD-5725 *(continued)*
  - Bridge submitted by Indiana DOT -- Single-span (35'-3") P/S spread box beams debonded strands
  - Significant reduction in shear-controlled load ratings between BrR v7.2 & v7.7

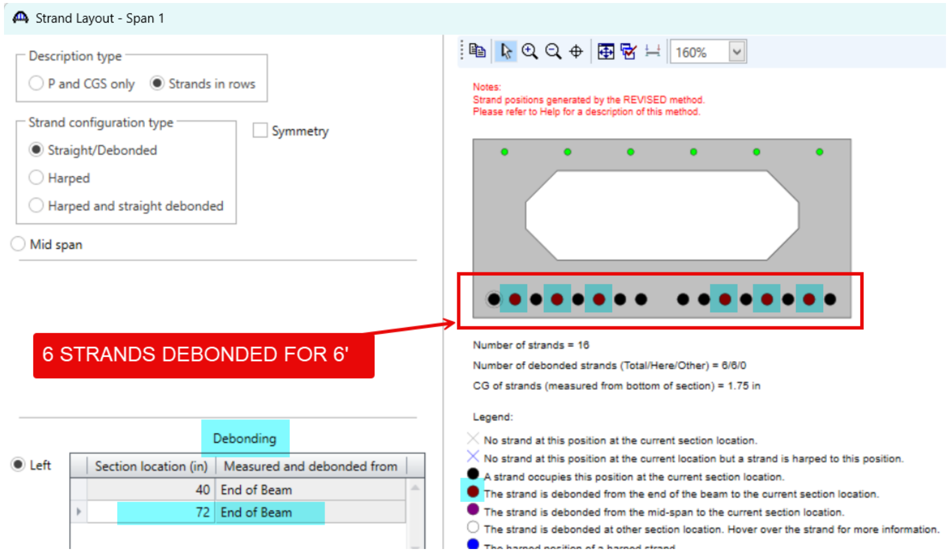


MCFT Issues in BrDR

- BSSD-5725 *(continued)*







MCFT Issues in BrDR

- BSSD-5725 *(continued)*

Spec Check Detail for 5.9.4.3.2 Bonded Strand

v7.2

```
5 Concrete Structures
5.9 Prestressing
5.9.4 Details for Pretensioning
5.9.4.3 Development of Prestressing Strand
5.9.4.3.2 Bonded Strand
(AASHTO LRFD Bridge Design Specifications, Ninth Edition)

PS Box Rect Void - At Location = 1.9502 (ft) - Right     Stage 3

ld >= k[fps - (2/3)fpe]db          (5.9.4.3.2-1)

Input:
fps              =   252.18 (ksi)    (Ave. stress in all strands at midspan)
fpe              =   147.18 (ksi)
db               =     0.50 (in)
Transfer Length  =    30.00 (in)

Strand Development Length Output:

Fully Bonded Strands
k  =     1.00
ld =    77.03 (in)

Partially Debonded Strands
k  =     2.00
ld =   154.06 (in)

Jacking Stress =   189.00 (ksi)
ES losses      =     0.00 (ksi)
Total losses   =    41.82 (ksi)
```

1.224 in^2

Group	Strand Group	Num Strands	Aps (in^2)	Lpx (in)	PS (Initial Loss) Stress (ksi)	PS (Initial Loss) Force (kip)	PS (Final Loss) Stress (ksi)	PS (Final Loss) Force (kip)	PS At Strength Stress (ksi)	PS At Strength Force (kip)
1	Debonded @ 3.33 LT	1	0.15	--	0.00	0.00	0.00	0.00	0.00	0.00
2	Debonded @ 6.00 LT	6	0.92	--	0.00	0.00	0.00	0.00	0.00	0.00
3	Debonded @ 3.33 LT	1	0.15	--	0.00	0.00	0.00	0.00	0.00	0.00
4	Straight	7	1.07	29.40	185.24	198.39	144.25	154.50	144.25	154.50
5	Debonded @ 0.00 LT	1	0.15	29.40	185.24	28.34	144.25	22.07	144.25	22.07
		16	2.45			226.73		176.57		176.57

Spec Check Detail for 5.9.4.3.2 Bonded Strand

v7.7.1

```
5 Concrete Structures
5.9 Prestressing
5.9.4 Details for Pretensioning
5.9.4.3 Development of Prestressing Strand
5.9.4.3.2 Bonded Strand
(AASHTO LRFD Bridge Design Specifications, Tenth Edition)

PS Box Rect Void - At Location = 1.9491 (ft) - Right     Stage 3

ld >= k[fps - (2/3)fpe]db          (5.9.4.3.2-1)

Input:
fps              =   253.15 (ksi)    (Ave. stress in all strands at midspan)
fpe              =   147.18 (ksi)
db               =     0.50 (in)
Transfer Length  =    30.00 (in)

Strand Development Length Output:

Fully Bonded Strands
k  =     1.00
ld =    77.52 (in)

Partially Debonded Strands
k  =     2.00
ld =   155.03 (in)

Jacking Stress               =   189.00 (ksi)
ES losses                    =     8.50 (ksi)
Long term losses (fpLT)      =    33.31 (ksi)
Total losses                 =    41.82 (ksi)
```

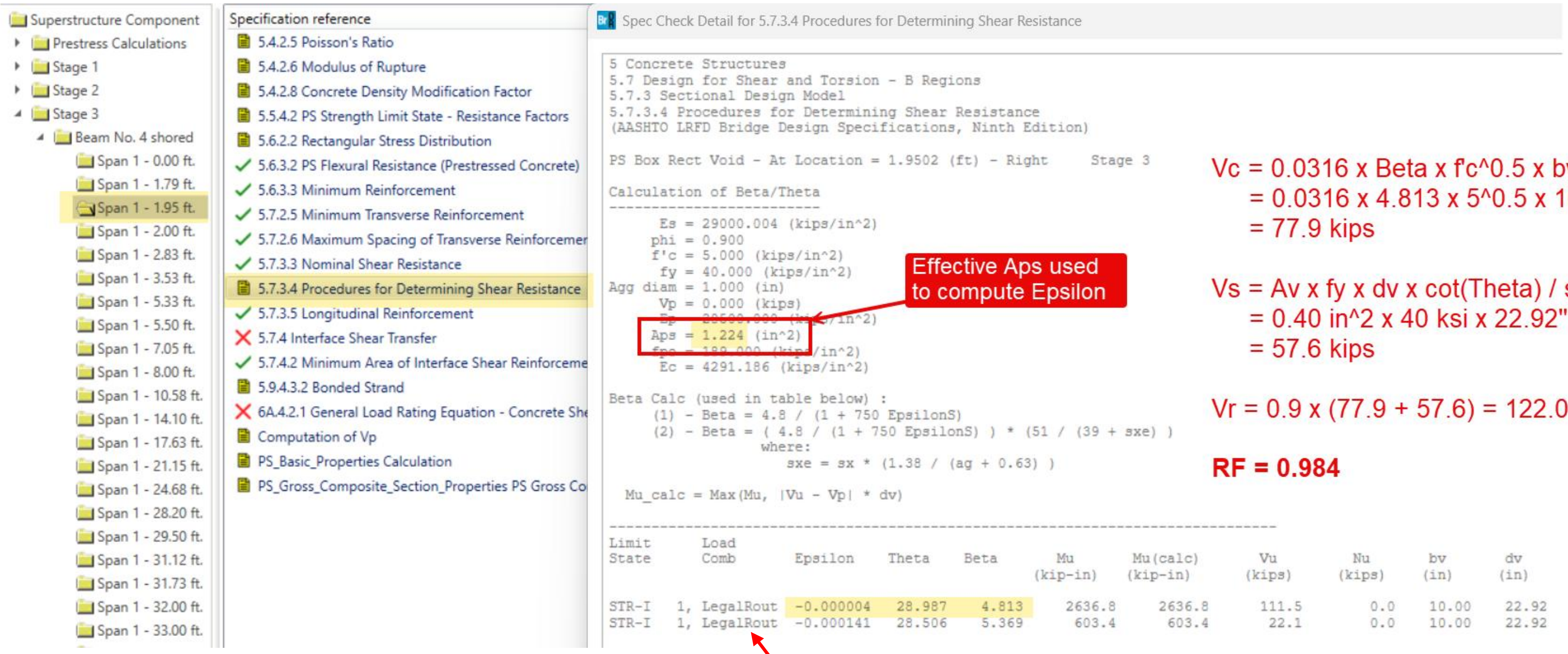
Row 4: 1.071 in^2 x 144.2 ksi / 253.1 ksi = 0.610 in^2
Row 5: 0.153 in^2 x 144.2 ksi / 253.1 ksi = 0.087 in^2
Total Eff Aps = 0.610 + 0.087 = 0.697 in^2

Group	Strand Group	Num Strands	Aps (in^2)	Lpx (in)	PS (Initial Loss) Stress (ksi)	PS (Initial Loss) Force (kip)	PS (Final Loss) Stress (ksi)	PS (Final Loss) Force (kip)	PS At Strength Stress (ksi)	PS At Strength Force (kip)
1	Debonded @ 3.33 LT	1	0.15	--	0.00	0.00	0.00	0.00	0.00	0.00
2	Debonded @ 6.00 LT	6	0.92	--	0.00	0.00	0.00	0.00	0.00	0.00
3	Debonded @ 3.33 LT	1	0.15	--	0.00	0.00	0.00	0.00	0.00	0.00
4	Straight	7	1.07	29.39	176.82	189.38	144.19	154.43	144.19	154.43
5	Debonded @ 0.00 LT	1	0.15	29.39	176.82	27.05	144.19	22.06	144.19	22.06
		16	2.45			216.43		176.49		176.49

```
Prestressed Effective Section Properties
----------------------------------------
Eff Aps = 0.6972 (in^2)
Eff CGS = 1.7500 (in)
Eff epg = 6.1296 (in)
Eff epc = 13.8936 (in)
```

MCFT Issues in BrDR

- BSSD-5725 *(continued)*



EV3 vehicle

v7.2

Vc = 0.0316 x Beta x f'c^0.5 x bv x dv
= 0.0316 x 4.813 x 5^0.5 x 10" x 22.92"
= 77.9 kips

Vs = Av x fy x dv x cot(Theta) / s
= 0.40 in^2 x 40 ksi x 22.92" / [tan(28.987) x 11.5"]
= 57.6 kips

Vr = 0.9 x (77.9 + 57.6) = 122.0 kips

RF = 0.984

MCFT Issues in BrDR

- BSSD-5725 *(continued)*

Superstructure Component
- Prestress Calculations
- Stage 1
- Stage 2
- Stage 3
  - Beam No. 4 shored
    - Span 1 - 0.00 ft.
    - Span 1 - 1.18 ft.
    - Span 1 - 1.95 ft.
    - Span 1 - 2.00 ft.
    - Span 1 - 2.83 ft.
    - Span 1 - 3.52 ft.
    - Span 1 - 5.33 ft.
    - Span 1 - 5.50 ft.
    - Span 1 - 7.05 ft.
    - Span 1 - 8.00 ft.
    - Span 1 - 10.57 ft.
    - Span 1 - 14.10 ft.
    - Span 1 - 17.62 ft.
    - Span 1 - 21.15 ft.
    - Span 1 - 24.68 ft.
    - Span 1 - 28.20 ft.
    - Span 1 - 29.50 ft.
    - Span 1 - 31.12 ft.
    - Span 1 - 31.72 ft.
    - Span 1 - 32.00 ft.
    - Span 1 - 33.00 ft.
    - Span 1 - 33.50 ft.
    - Span 1 - 34.58 ft.
    - Span 1 - 35.25 ft.

Specification reference
- 5.4.2.5 Poisson's Ratio
- 5.4.2.6 Modulus of Rupture
- 5.4.2.8 Concrete Density Modification Factor
- 5.5.4.2 PS Strength Limit State - Resistance Factors
- 5.6.2.2 Rectangular Stress Distribution
- 5.6.3.2 PS Flexural Resistance (Prestressed Concrete)
- 5.6.3.3 Minimum Reinforcement
- 5.7.4 Interface Shear Transfer
- 5.7.4.2 Minimum Area of Interface Shear Reinforcement
- 5.9.4.3.2 Bonded Strand
- 6A.4.2.1 General Load Rating Equation - Concrete Shear
- 6A.4.2.1 Shear-5.6.3.3 Minimum Reinforcement
- 6A.4.2.1 Shear-5.7.2.5 Minimum Transverse Reinforcement
- 6A.4.2.1 Shear-5.7.2.6 Maximum Spacing of Transverse Reinforcemer
- 6A.4.2.1 Shear-5.7.3.3 Nominal Shear Resistance
- 6A.4.2.1 Shear-5.7.3.4 Procedures for Determining Shear Resistance
- Computation of Vp
- PS_Basic_Properties Calculation
- PS_Gross_Composite_Section_Properties PS Gross Composite Sectior

Spec Check Detail for 6A.4.2.1 Shear-5.7.3.4 Procedures for Determining Shear Resistance

```
6A.4.2.1 Shear - 5 Concrete Structures
6A.4.2.1 Shear - 5.7 Shear and Torsion
6A.4.2.1 Shear - 5.7.3 Sectional Design Model
6A.4.2.1 Shear - 5.7.3.4 Procedures for Determining Shear Resistance
(AASHTO Manual for Bridge Evaluation, Third Edition with 2024 Interims)

PS Box Rect Void - At Location = 1.9491 (ft) - Right     Stage 3

Calculation of Beta/Theta
-------------------------

      Es = 29000.004 (kips/in^2)
     phi = 0.900
     f'c = 5.000 (kips/in^2)
     fpc = 0.180 (kips/in^2)
      fy = 40.000 (kips/in^2)
Agg diam = 1.000 (in)
      Vp = 0.000 (kips)
      Ep = 28500.000 (kips/in^2)
 As(pos) = 0.000 (in^2)   (used for Positive Mu)
 As(neg) = 1.000 (in^2)   (used for Negative Mu)
Aps(pos) = 0.697 (in^2)   (used for Positive Mu)
Aps(neg) = 0.000 (in^2)   (used for Negative Mu)
     fpo = 189.000 (kips/in^2)
      Ec = 4291.186 (kips/in^2)

Beta Calc (used in table below) :
     (1) - Beta = 4.8 / (1 + 750 EpsilonS)
     (2) - Beta = ( 4.8 / (1 + 750 EpsilonS) ) * (51 / (39 + sxe) )
                where:
                   sxe = sx * (1.38 / (ag + 0.63) )

  Mu_calc = Max(Mu, |Vu - Vp| * dv)

Modify MCFT Theta:   No

Modify MCFT Size Effect:   No
fpc / f'c = 0.04
```

Limit State	Load Comb	Epsilon	Theta	Beta	Governing Action	Mu (kip-in)	Mu Calc (kip-in)	Vu (kips)	Nu (kips)	bv (in)	dv (in)
STR-I	1, LegalRo~	0.004645	45.26	1.07	Max M	2635.31	2635.31	109.09	0.00	10.00	22.92
STR-I	1, LegalRo~	-0.000066	28.77	5.05	Min M	603.03	603.03	24.41	0.00	10.00	22.92
STR-I	1, LegalRo~	0.004765	45.68	1.05	Max V	2635.31	2635.31	111.47	0.00	10.00	22.92
STR-I	1, LegalRo~	-0.000035	28.88	4.93	Min V	1521.99	1521.99	22.11	0.00	10.00	22.92
SER-III	1, LegalRo~	-0.000019	28.93	4.87	Max M	2045.71	2045.71	19.53	0.00	10.00	22.92

v7.7.1

Effective Aps used to compute Epsilon

EV3 vehicle

Vc = 0.0316 x Beta x f'c^0.5 x bv x dv
= 0.0316 x 1.05 x 5^0.5 x 10" x 22.92"
= 17.0 kips

Vs = Av x fy x dv x cot(Theta) / s
= 0.40 in^2 x 40 ksi x 22.92" / [tan(45.68) x 12"]
= 29.83 kips

Vr = 0.9 x (17.0 + 29.8) = 42.1 kips

RF = 0.155

MCFT Issues in BrDR

- BSSD-5758 Assuming longitudinal strain = 0 when $M_u < M_{cr}$ -- differences between Art. 5.7.3.4.2 & Appendix B5.2
  - 2022 AASHTO Agenda Item 50 Sub-item #2
  - Allows LRFD Article 5.7.3.4.2 to be modified for the purpose of load rating
  - If section remains uncracked at strength limit state ($M_u < M_{cr}$), the longitudinal strain, ε_s, can be assumed to be zero.
  - Passed agenda item did not reference Appendix B5.2, therefore not implemented in BrDR for that shear method option
  - Not applying same provision when Appendix B5.2 shear method can result in significant shear load rating discrepancies.

2022 AASHTO BRIDGE COMMITTEE AGENDA ITEM: 50

SUBJECT: The Manual for Bridge Evaluation: Section 6, Articles C6A.4.2.1 and 6A5.8 (T18-01)

TECHNICAL COMMITTEE: T-18 Bridge Management, Evaluation and Rehabilitation

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☒ REVISION ☒ ADDITION ☐ NEW DOCUMENT

Item #2

In Article 6A.5.8, revise the 2nd paragraph and add the following after the 2nd paragraph:

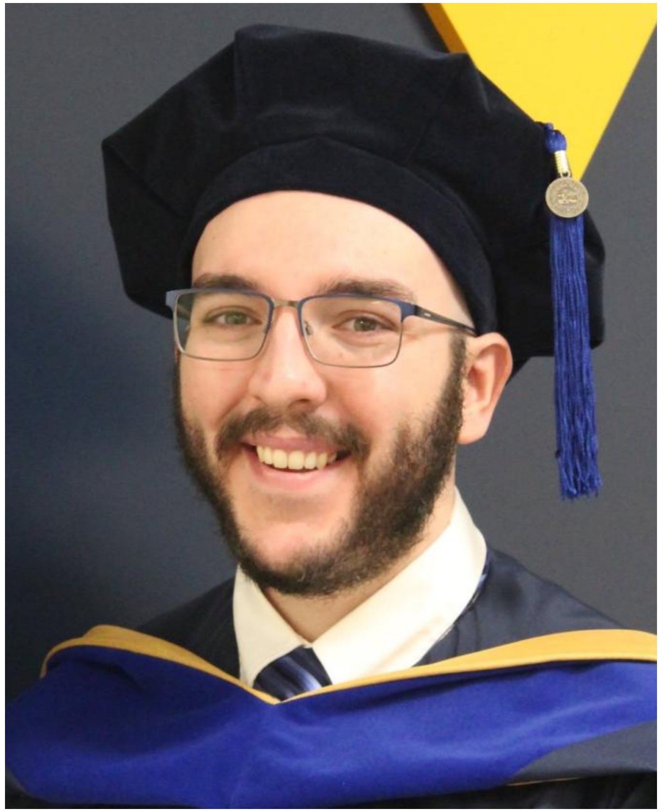
When using the Modified Compression Field Theory (MCFT) for the evaluation of concrete shear resistance, the longitudinal reinforcement should be checked for the increased tension caused by shear, in accordance with LRFD

For the purposes of load rating and application of MCFT it is permissible to modify the LRFD Article 5.7.3.4.2 as follows:

1. In areas of low strain where the section remains uncracked, that is $M_u < M_{cr}$, the strain ε_s may be assumed to be zero regardless of values of M_u and V_u; therefore, θ can be taken as 29 degrees.
2. For reinforced concrete members with web reinforcement $A_v < A_{v,min}$, the beta should be adjusted by applying the size effect. For prestressed concrete beams, if f_{pc}/f'_c is greater than or equal to 0.02, regardless of the

MCFT Issues in BrDR

DR ROBBY'S FAVORITE MBE PROVISION & BrDR CONTROL OPTION

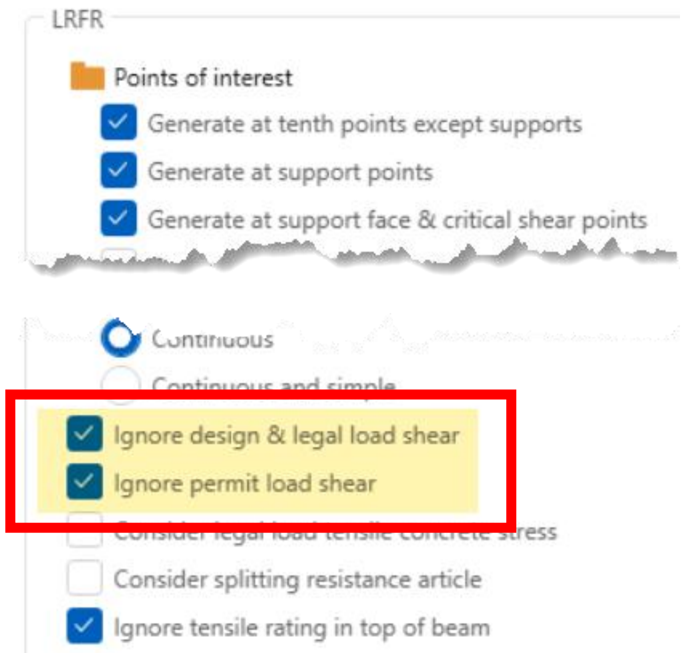


DR ROBBY TENNANT

6A.5.8—Evaluation for Shear

The shear capacity of existing reinforced and prestressed concrete bridge members should be evaluated for permit loads. In-service concrete bridges that show no visible signs of shear distress need not be checked for shear when rating for the design load or legal loads.

When using the Modified Compression Field Theory (MCFT) for the evaluation of concrete shear resistance, the longitudinal reinforcement should be checked for the increased tension caused by shear, in accordance with LRFD Design Article 5.7.3.6.3.



THANK YOU!

QUESTIONS?