LRFD, The USA’s Innovative Bridge Design Specifications

Firas I. Sheikh Ibrahim, Ph.D., P.E.

Senior Codes & Specifications Engineer

Office of Bridge Technology
Federal Highway Administration
Washington, DC

U.S. Department of Transportation
Federal Highway Administration

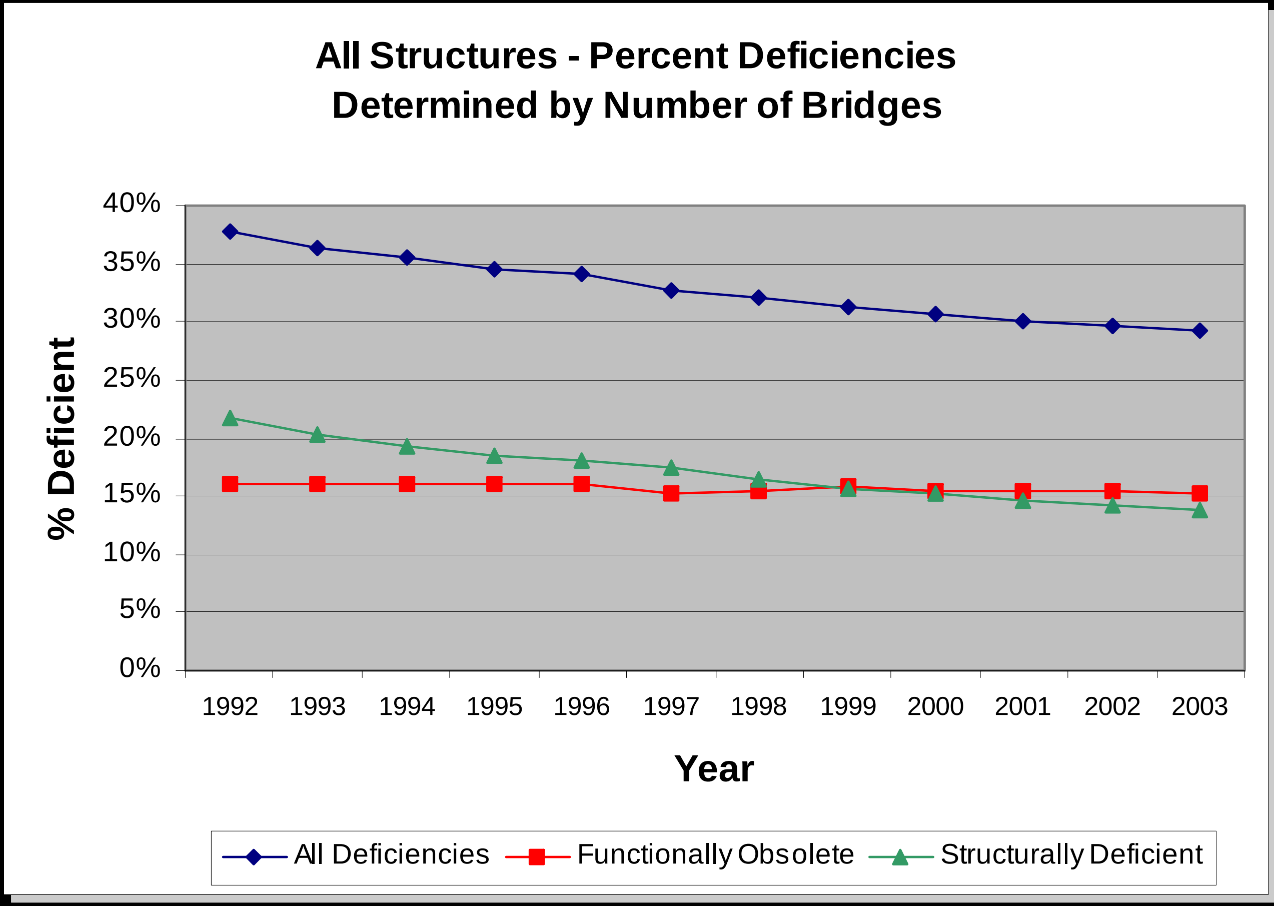
Who We Are, at FHWA

A USDOT Agency responsible for ensuring that America's roads and highways continue to be the safest and most technologically up-to-date.

We provide financial (> $30 Billion/year) and technical support to States and Local Governments

Effect of Federal Aid on Transportation Structures

Federal Aid has been increasing significantly (\$14,257,907,017 in ISTEA *To* \$23,365,688,795 in TEA21)*, but deficiencies remain significant*



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FHWA's Top Priorities

✓*Make transportation safer, more reliable and secure,*

✓*Reduce traffic congestion, and*

✓*Minimize impact on the environment*

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LRFD

Accomplishment of Top Priorities

1-Develop and Deploy Reliable and Safer Specifications, and increase the Design and Service Life

✓Safer

✓Reduce congestion

✓Minimize impact on the environment

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Evolution Of Design Specifications

1931 - First AASHO Specs

Evolved into AASHTO Standard Specs (SLD, and LFD), and became a patch document with inconsistencies and gaps

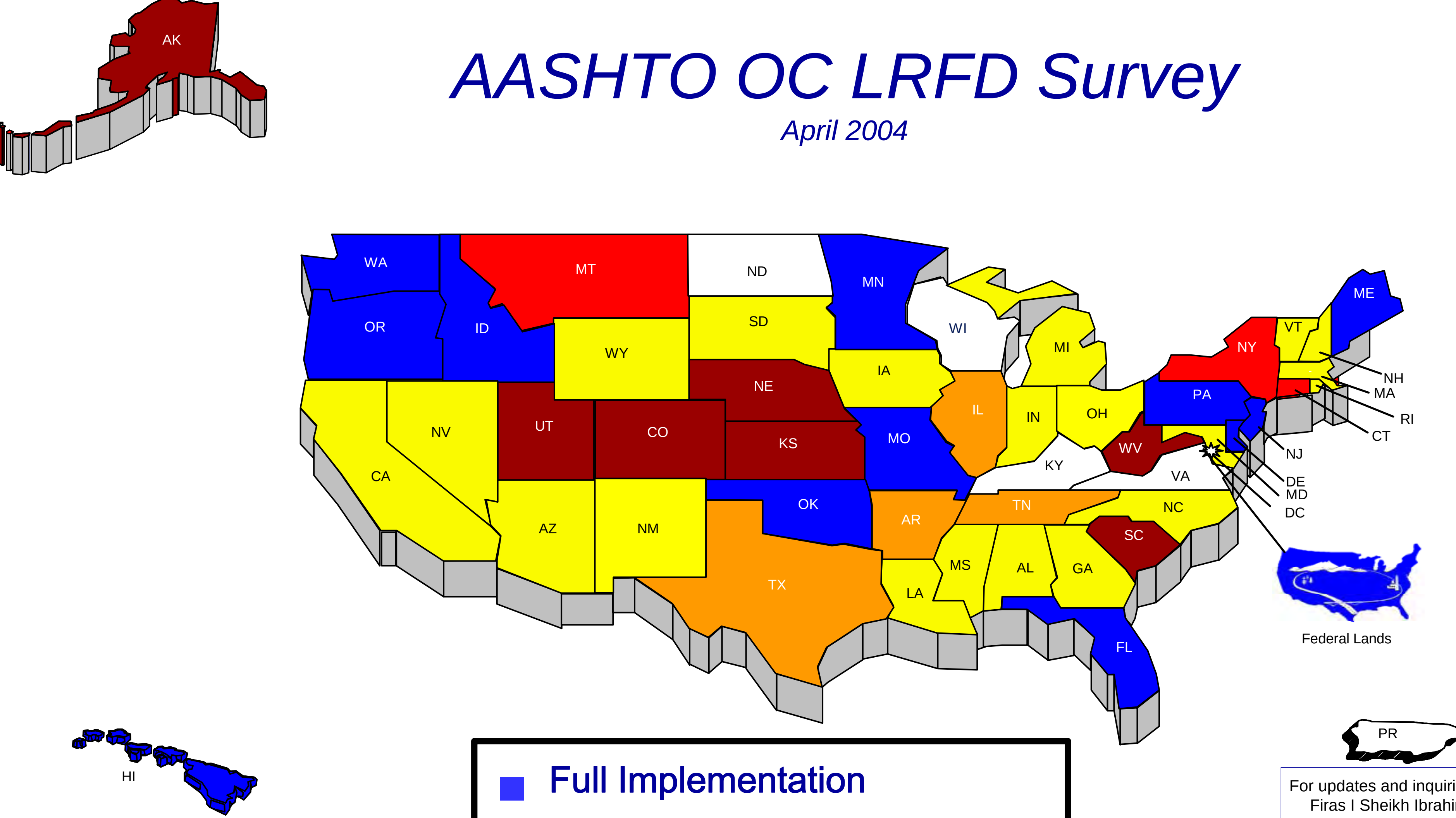
1994 - Load and Resistance Factor Design (LRFD)

1998 - 2nd Edition of LRFD

2004 - 3rd Edition of LRFD

AASHTO OC LRFD Survey

April 2004



- Full Implementation
- 50-90% Partial Implementation
- 26-50% Partial Implementation
- 11-25% Partial Implementation
- 1-10% Partial Implementation
- No Implementation

For updates and inquiries, contact:
Firas I Sheikh Ibrahim, PhD, PE
LRFD Engineer
Federal Highway Administration
Office of Bridge Technology
HIBT-10, Room 3203
400 7th. St. SW
Washington, DC 20590
(202)-366-4598 Direct
(202)-366-4589 Main Office
(202)-366-3077 Fax
Firas.Ibrahim@ fhwa .dot. gov
http://www. fhwa .dot. gov /Bridge/

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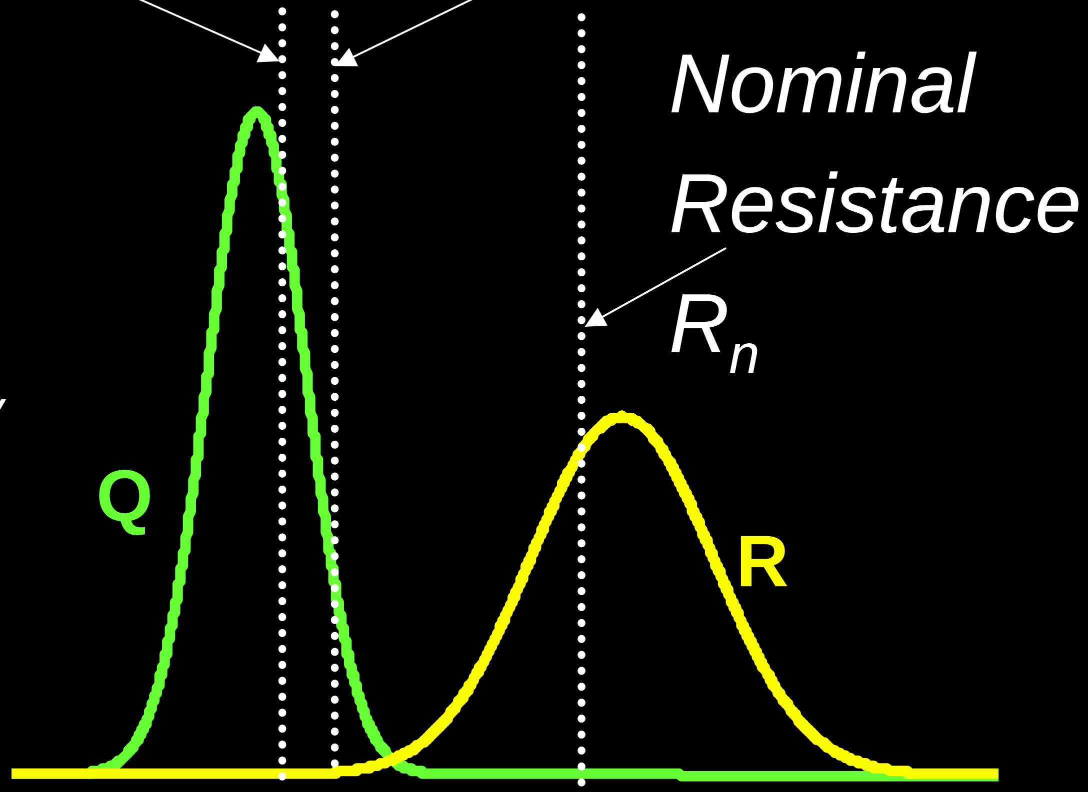
Service Load DESIGN

Nominal Load Effect, $Q_n \le \dfrac{R_n}{FS}$

<u>Service Load Design (SLD):</u>

$(f_t)_D + (f_t)_L \le 0.55F_y$, or

$1.82(f_t)_D + 1.82(f_t)_L \le F_y$



LFD Design Equation

$$\Sigma \gamma_i Q_i \leq \phi R_n$$

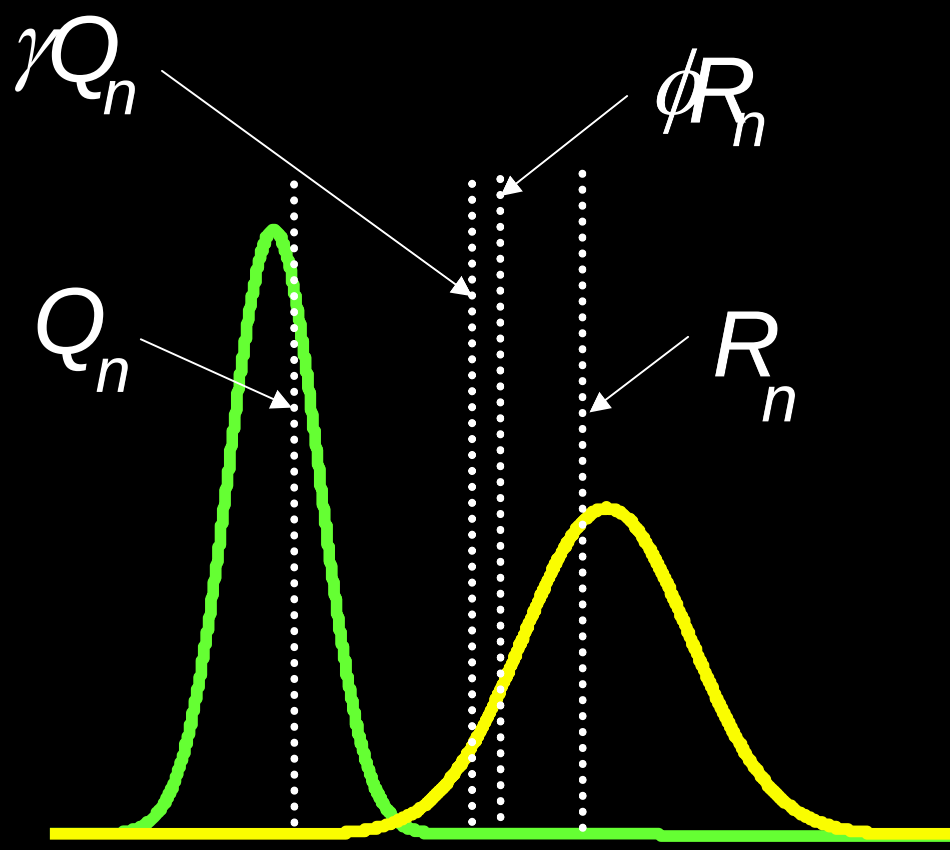
where:

γ_i = *Load factor*

$\gamma_i Q_i$ = *Factored load, required capacity*

ϕ = *Resistance factor*

ϕR_n = *Capacity*



Load Factor Design (LFD):

$$1.3[1.0(f_t)_D + 5/3(f_t)_L] \leq \phi F_y, \text{ or}$$

$$1.3(f_t)_D + 2.17(f_t)_L \leq \phi F_y$$ *(ϕ by judgment)*

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Design & Service Life for The Standard Specifications

Design Life is 50 years

Service Life could be less than 50

Innovative LRFD Design Specifications

- ✓ Longer Design Life (75 years)
- ✓ Allows use of High Performance Material; Service Life (>75 years)
- ✓ Consistent Reliability and Safety Factors for all bridges,
- ✓ More Realistic Live Load Model, and Distribution Factors
- ✓ State of the Art Provisions and Design Procedures

Basic LRFD Design Equation

$$\Sigma\, \eta_i\, \gamma_i\, Q_i \leq \phi R_n = R_r$$

where:

η_i = $\eta_D\, \eta_R\, \eta_I$

η_i = *Load modifier*

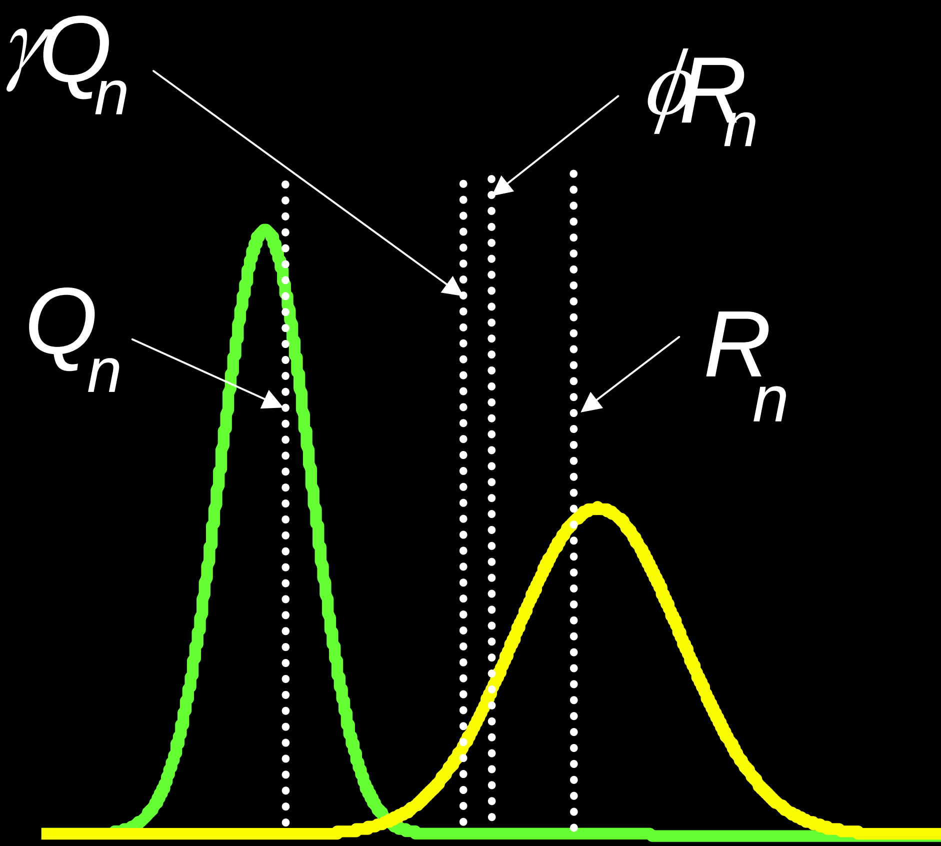
γ_i = *Load factor*

Q_i = *Nominal force effect*

ϕ = *Resistance factor*

R_n = *Nominal resistance*

R_r = *Factored resistance* = ϕR_n



Sample LRFD Design Equation:

$$1.25(f_t)_D + 1.75(f_t)_L \leq \phi F_y$$ *(ϕ by calibration)*

(new live-load model)

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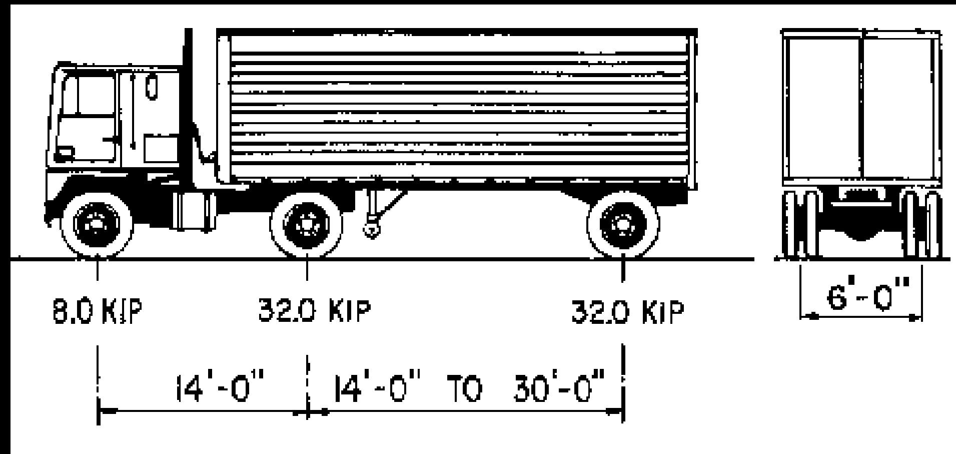
LRFD = More Accurate Live Load Model, HL-93

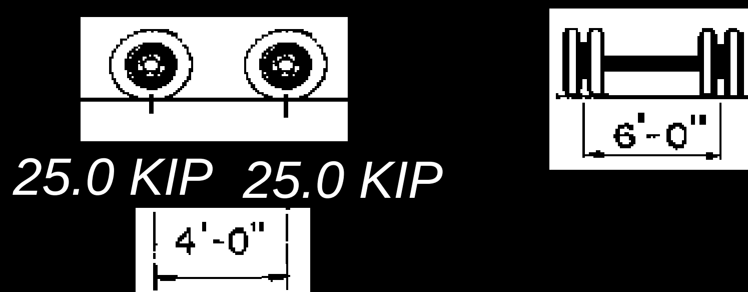
- *Design Truck:* ⇒



or

or

- *Design Tandem:*
  Pair of 25.0 KIP axles spaced 4.0 FT apart



superimposed on

+

- *Design Lane Load* *0.64 KLF uniformly distributed load*

0.64 Kip/ft

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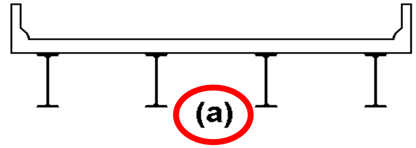
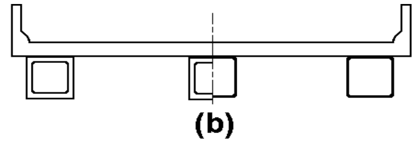
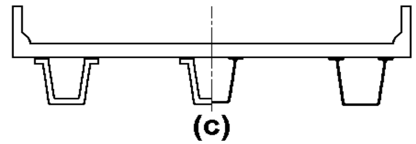
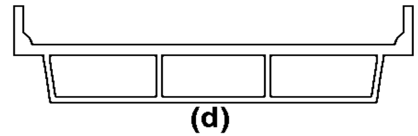
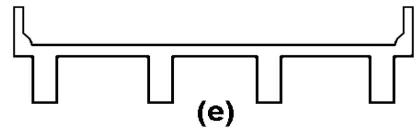
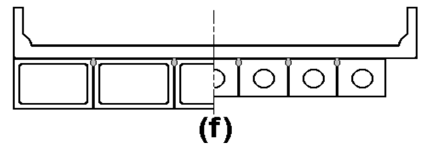
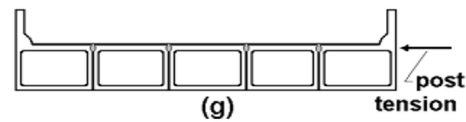
LRFD = More Accurate Live-Load Distribution Factors

TABLE 4.6.2.2.1-1 COMMON DECK SUPERSTRUCTURES COVERED IN ARTICLES 4.6.2.2.2 AND 4.6.2.2.3.

SUPPORTING COMPONENTS	TYPE OF DECK	TYPICAL CROSS-SECTION
Steel Beam	Cast-in-place concrete slab, precast concrete slab, steel grid, glued/spiked panels, stressed wood	 (a)
Closed Steel or Precast Concrete Boxes	Cast-in-place concrete slab	 (b)
Open Steel or Precast Concrete Boxes	Cast-in-place concrete slab, precast concrete deck slab	 (c)
Cast-in-Place Concrete Multicell Box	Monolithic concrete	 (d)
Cast-in-Place Concrete Tee Beam	Monolithic concrete	 (e)
Precast Solid, Voided or Cellular Concrete Boxes with Shear Keys	Cast-in-place concrete overlay	 (f)
Precast Solid, Voided, or Cellular Concrete Box with Shear Keys and with or without Transverse Posttensioning	Integral concrete	 (g)

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Sample Live-Load Distribution Factors (Moments – Interior Beams)

Table 4.6.2.2.2b-1 Distribution of Live Loads Per Lane for Moment in Interior Beams.

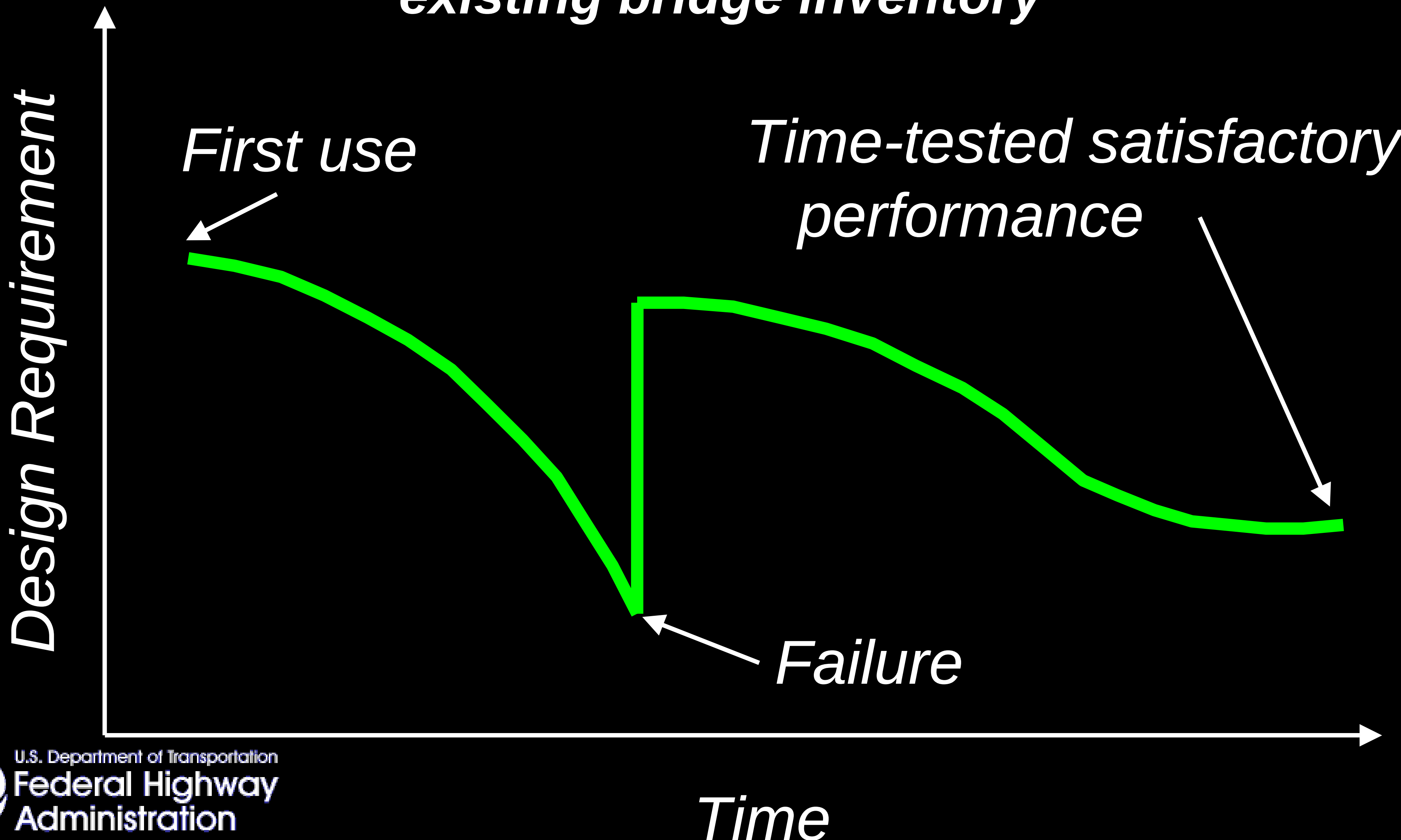
Type of Beams	Applicable Cross-Section from Table 4.6.2.2.1-1	Distribution Factors	Range of Applicability
Concrete Deck, Filled Grid, Partially Filled Grid, or Unfilled Grid Deck Composite with Reinforced Concrete Slab on Steel or Concrete Beams; Concrete T-Beams, T- and Double T-Sections	a, e, k and also i, j if sufficiently connected to act as a unit	One Design Lane Loaded: $0.06+\left(\frac{S}{14}\right)^{0.4}\left(\frac{S}{L}\right)^{0.3}\left(\frac{K_g}{12.0Lt_s^3}\right)^{0.1}$ Two or More Design Lanes Loaded: $0.075+\left(\frac{S}{9.5}\right)^{0.6}\left(\frac{S}{L}\right)^{0.2}\left(\frac{K_g}{12.0\,Lt_s^3}\right)^{0.1}$	$3.5 \le S \le 16.0$ $20 \le L \le 240$ $4.5 \le t_s \le 12.0$ $N_b \ge 4$ $10{,}000 \le K_g \le 7{,}000{,}000$
		use lesser of the values obtained from the equation above with $N_b = 3$ or the lever rule	$N_b = 3$

<u>Notes</u>: 1) Units are in LANES and not WHEELS

2) No multiple presence factor applied (tabulated equations)

LRFD Calibration is Scientific

& based on performance of prior design specs & existing bridge inventory



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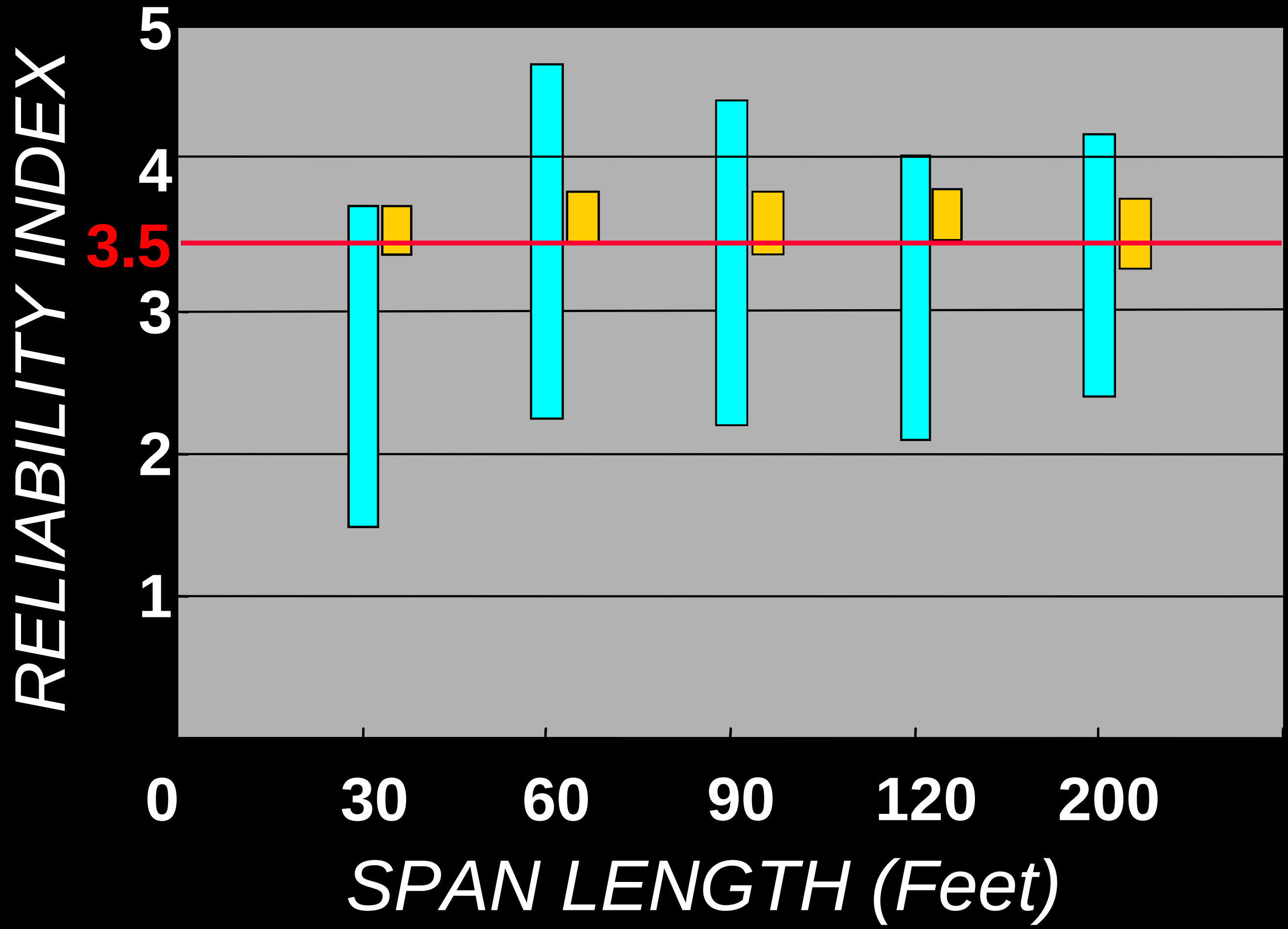
Reliability and Calibration of Standard & LRFD Specifications



NORMALLY DISTRIBUTED Q AND R:

$$\beta = \frac{\bar{R} - \bar{Q}}{\sqrt{\sigma_R^2 + \sigma_Q^2}}$$

LOGNORMALLY DISTRIBUTED Q AND R

$$\beta = \frac{\ln\left(\frac{\bar{R}}{\bar{Q}}\right)}{\sqrt{V_R^2 + V_Q^2}}$$

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States' Experience with the AASHTO LRFD Design Specifications

(>2,240 LRFD Bridges – 2004)

Doremus Avenue Viaduct (Newark, NJ)

Rt. 9, Nacote Creek Bridge (South Jersey)

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Barclay Creek Bridge Site

- ✓ *Environmentally sensitive area*
- ✓ *170 foot span required for hydraulic requirements*

- ✓ *HPS 70W LRFD Bridge*
- ✓ *174 foot span length*

- ✓ *Overall, a good experience*

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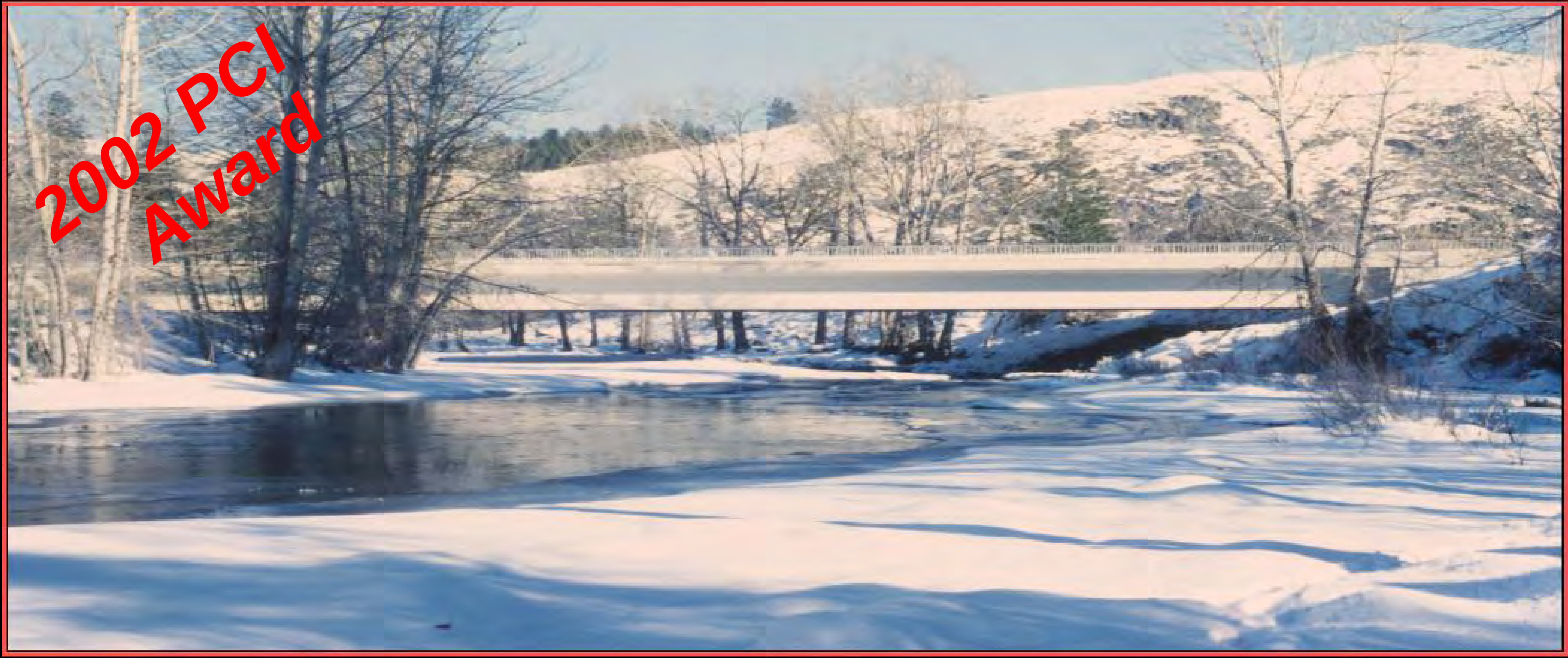
WSDOT Spliced I-Girders
Twisp River Bridge, Twisp, WA



Single-span spliced concrete girders spanning 195 ft

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Washington State Department of Transportation

FLDOT
St. George Island Bridge Apalachicola, FL

- ✓ *21,542' long* bridge
- ✓ *Post-tensioned bulb-tee girders*

FLDOT
Hathaway Bridge , Panama City, FL

- ✓ 3,815’ long
- ✓ 330’ typical span
  Segmental boxes

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Long Span Bridges in LRFD?
(Great River Bridge, Desha County, AR)

682 ft - 1,520 ft – 682 ft Cable-Stay Bridge

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Long Span Bridges in LRFD? (Hoover Dam Bypass Project)

Composite Concrete Deck Arch Bridge

(~2,000 ft)

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Some State DOT's Conclusion

✓ New Jersey:	".. major step forward .."
	".. cost savings of up to 8 percent .."
✓ Washington:	".. good experience … was not so difficult.."
	".. comprehensive …. powerful .."
✓ Florida:	".. good experience … was not so difficult.."
	".. comprehensive …. powerful .."

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Reliability = LRFD

SUMMARY
LRFD

- ✓*Comprehensive, rational, and powerful specs*
- ✓*Result in safer and more reliable transportation structures*
- ✓*Design Life is 75 years*

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FREE Assistance from Uncle SAM

THANK YOU

Firas I. Sheikh Ibrahim, Ph.D., P.E.

Senior Codes & Specifications Engineer

Office of Bridge Technology

Federal Highway Administration

HIBT-10, Room 3203

400 7th. St. SW

Washington, DC 20590

(202) 366-4598

Firas.Ibrahim@fhwa.dot.gov

LRFD
Loads and
Loads Distribution

Firas I. Sheikh Ibrahim, Ph.D., P.E.
Federal Highway Administration
Washington, DC

Basic LRFD Design Equation

$$\Sigma\ \eta_i \gamma_i Q_i \leq \phi R_n = R_r$$ **Eq. (1.3.2.1-1)**

where:

η_i = $\eta_D\ \eta_R\ \eta_I$

γ_i = **Load factor**

ϕ = **Resistance factor**

Q_i = **Nominal force effect**

R_n = **Nominal resistance**

R_r = **Factored resistance** = ϕR_n

Load Combinations and Load Factors

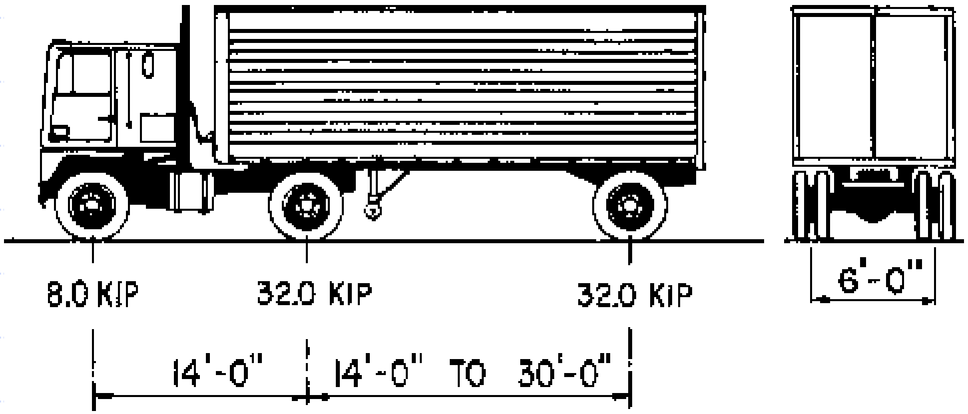
Load Combination / Limit State	DC DD DW EH EV ES	LL IM CE BR PL LS	WA	WS	WL	FR	TU CR SH	TG	SE	Use One of These at a Time			
										EQ	IC	CT	CV
STRENGTH-I	γ_p	1.75	1.00	-	-	1.00	0.50/1.20	γ_{TG}	γ_{SE}	-	-	-	-
STRENGTH-II	γ_p	1.35	1.00	-	-	1.00	0.50/1.20	γ_{TG}	γ_{SE}	-	-	-	-
STRENGTH-III	γ_p	-	1.00	1.40	-	1.00	0.50/1.20	γ_{TG}	γ_{SE}	-	-	-	-
STRENGTH-IV EH, EV, ES, DW DC ONLY	γ_p 1.5	-	1.00	-	-	1.00	0.50/1.20	-	-	-	-	-	-
STRENGTH-V	γ_p	1.35	1.00	0.40	1.00	1.00	0.50/1.20	γ_{TG}	γ_{SE}	-	-	-	-
EXTREME-I	γ_p	γ_{EQ}	1.00	-	-	1.00	-	-	-	1.00	-	-	-
EXTREME-II	γ_p	0.50	1.00	-	-	1.00	-	-	-	-	1.00	1.00	1.00
SERVICE-I	1.00	1.00	1.00	0.30	0.30	1.00	1.00/1.20	γ_{TG}	γ_{SE}	-	-	-	-
SERVICE-II	1.00	1.30	1.00	-	-	1.00	1.00/1.20	-	-	-	-	-	-
SERVICE-III	1.00	0.80	1.00	-	-	1.00	1.00/1.20	γ_{TG}	γ_{SE}	-	-	-	-
FATIGUE-LL, IM & CE ONLY	-	0.75	-	-	-	-	-	-	-	-	-	-	-

Load Factors for Permanent Loads, γ_p

Type of Load	Load Factor	
	Maximum	Minimum
DC: Component and Attachments	1.25	0.90
DD: Downdrag	1.80	0.45
DW: Wearing Surfaces and Utilities	1.50	0.65
EH: Horizontal Earth Pressure		
• Active	1.50	0.90
• At-Rest	1.35	0.90
EV: Vertical Earth Pressure		
• Overall Stability	1.35	N/A
• Retaining Structure	1.35	1.00
	1.30	0.90
• Rigid Buried Structure	1.35	0.90
• Rigid Frames	1.95	0.90

Basic LRFD Design Live Load
HL-93 -- (Article 3.6.1.2.1)

- **Design Truck:** ⇒



or

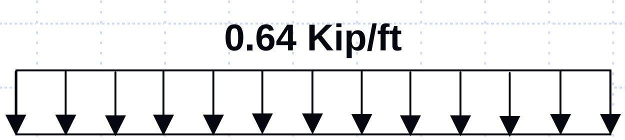
or

- **Design Tandem:**
  Pair of 25.0 KIP axles spaced 4.0 FT apart

superimposed on

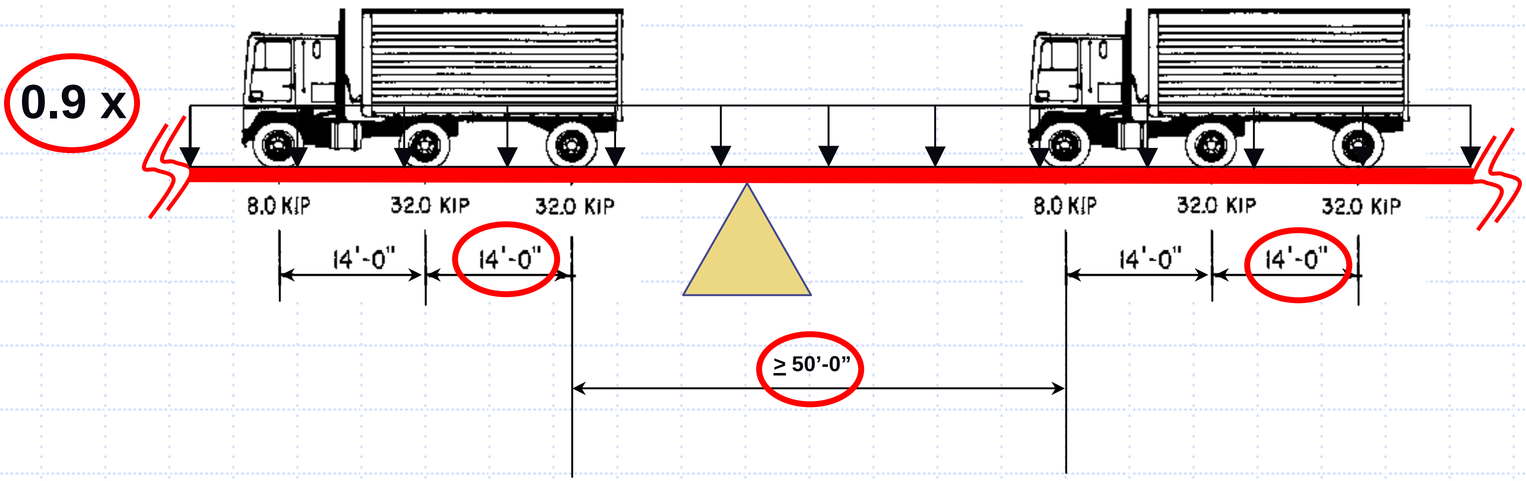
+

- **Design Lane Load** **0.64 KLF uniformly distributed load**



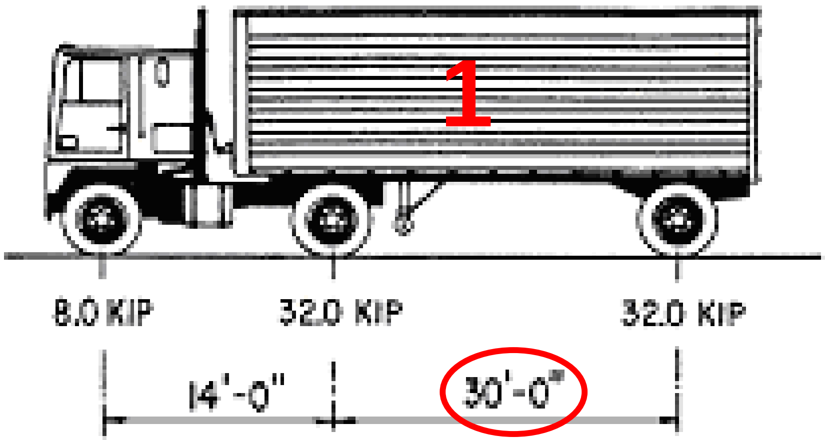
LRFD Negative Moment Loading (Article 3.6.1.3.1)

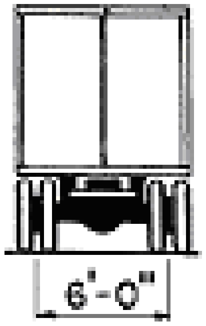
- For negative moment (between points of permanent-load contraflexure) & interior-pier reactions, check an additional load case:



LRFD Fatigue Load
(Article 3.6.1.4.1)

- **Design Truck only =>**
  - **w/ fixed 30-ft rear-axle spacing**
  - **Placed in a single lane**





Section 4

Structural Analysis and Evaluation

4.6 Static Analysis

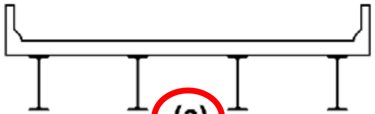
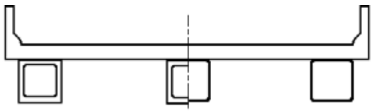
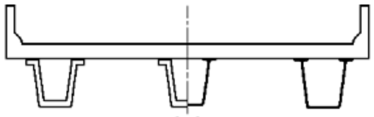
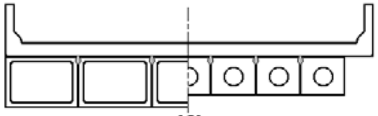
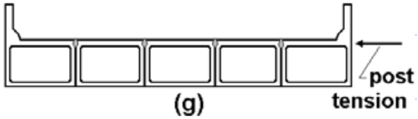
4.6.2 Approximate Methods of Analysis

4.6.2.2 Beam-Slab Bridges

⇓

Live-Load Lateral Distribution Factors

TABLE 4.6.2.2.1-1 COMMON DECK SUPERSTRUCTURES COVERED IN ARTICLES 4.6.2.2.2 AND 4.6.2.2.3.

SUPPORTING COMPONENTS	TYPE OF DECK	TYPICAL CROSS-SECTION
Steel Beam	Cast-in-place concrete slab, precast concrete slab, steel grid, glued/spiked panels, stressed wood	 (a)
Closed Steel or Precast Concrete Boxes	Cast-in-place concrete slab	 (b)
Open Steel or Precast Concrete Boxes	Cast-in-place concrete slab, precast concrete deck slab	 (c)
Cast-in-Place Concrete Multicell Box	Monolithic concrete	 (d)
Cast-in-Place Concrete Tee Beam	Monolithic concrete	 (e)
Precast Solid, Voided or Cellular Concrete Boxes with Shear Keys	Cast-in-place concrete overlay	 (f)
Precast Solid, Voided, or Cellular Concrete Box with Shear Keys and with or without Transverse Posttensioning	Integral concrete	 (g)

Live-Load Distribution Factors Moments – Interior Beams

Table 4.6.2.2.2b-1 Distribution of Live Loads Per Lane for Moment in Interior Beams.

Type of Beams	Applicable Cross-Section from Table 4.6.2.2.1-1	Distribution Factors	Range of Applicability
Concrete Deck, Filled Grid, Partially Filled Grid, or Unfilled Grid Deck Composite with Reinforced Concrete Slab on Steel or Concrete Beams; Concrete T-Beams, T- and Double T-Sections	a, e, k and also i, j if sufficiently connected to act as a unit	One Design Lane Loaded: $0.06+\left(\frac{S}{14}\right)^{0.4}\left(\frac{S}{L}\right)^{0.3}\left(\frac{K_g}{12.0Lt_s^{\,3}}\right)^{0.1}$ Two or More Design Lanes Loaded: $0.075+\left(\frac{S}{9.5}\right)^{0.6}\left(\frac{S}{L}\right)^{0.2}\left(\frac{K_g}{12.0\,Lt_s^{\,3}}\right)^{0.1}$	$3.5 \le S \le 16.0$ $20 \le L \le 240$ $4.5 \le t_s \le 12.0$ $N_b \ge 4$ $10{,}000 \le K_g \le 7{,}000{,}000$
		use lesser of the values obtained from the equation above with $N_b = 3$ or the lever rule	$N_b = 3$

Notes: 1) Units are in LANES and not WHEELS!

2) No multiple presence factor applied (tabulated equations)

3) May be Different for Positive and Negative Flexure Locations!

Live-Load Distribution Factors Shear – Interior Beams

Table 4.6.2.2.3a-1 Distribution of Live Load per Lane for Shear in Interior Beams.

Type of Superstructure	Applicable Cross-Section from Table 4.6.2.2.1-1	One Design Lane Loaded	Two or More Design Lanes Loaded	Range of Applicability
Concrete Deck, Filled Grid, Partially Filled Grid, or Unfilled Grid Deck Composite with Reinforced Concrete Slab on Steel or Concrete Beams; Concrete T-Beams, T-and Double T-Sections	a, e, k and also i, j if sufficiently connected to act as a unit	$0.36+\frac{S}{25.0}$	$0.2+\frac{S}{12}-\left(\frac{S}{35}\right)^{2.0}$	$3.5 \le S \le 16.0$ $20 \le L \le 240$ $4.5 \le t_s \le 12.0$ $N_b \ge 4$
		Lever Rule	Lever Rule	$N_b = 3$

Notes: Same for Positive and Negative Flexure Locations!

Live-Load Distribution Factors Moments – Exterior Beams

Table 4.6.2.2.2d-1 Distribution of Live Loads Per Lane for Moment in Exterior Longitudinal Beams.

Type of Superstructure	Applicable Cross-Section from Table 4.6.2.2.1-1	One Design Lane Loaded	Two or More Design Lanes Loaded	Range of Applicability
Concrete Deck, Filled Grid, Partially Filled Grid, or Unfilled Grid Deck Composite with Reinforced Concrete Slab on Steel or Concrete Beams; Concrete T-Beams, T- and Double T- Sections	a, e, k and also i, j if sufficiently connected to act as a unit	Lever Rule	$g = e\, g_{interior}$ $e = 0.77 + \frac{d_e}{9.1}$	$-1.0 \le d_e \le 5.5$
			use lesser of the values obtained from the equation above with $N_b = 3$ or the lever rule	$N_b = 3$

Notes: distribution factor for the exterior beam shall not be taken to be less than that which would be obtained by assuming that the cross-section deflects and rotates as a rigid cross-section (SPECIAL ANALYSIS).

$$R = \frac{N_L}{N_b} + \frac{X_{ext} \sum^{N_L} e}{\sum^{N_b} x^2}$$

Live-Load Distribution Factors
Shear – Exterior Beams

Table 4.6.2.2.3b-1 Distribution of Live Load per Lane for Shear in Exterior Beams.

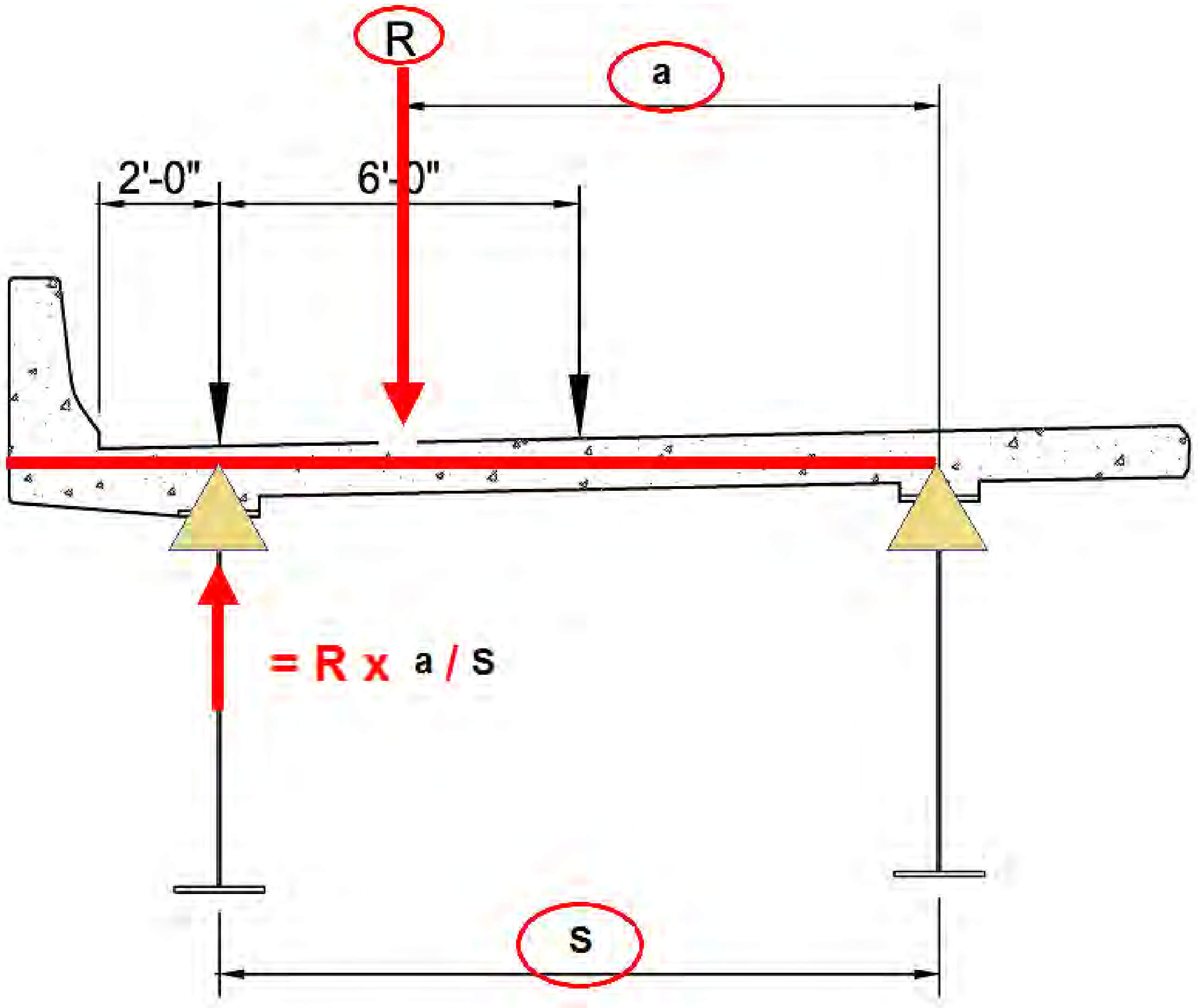
Type of Superstructure	Applicable Cross-Section from Table 4.6.2.2.1-1	One Design Lane Loaded	Two or More Design Lanes Loaded	Range of Applicability
Concrete Deck, Filled Grid, Partially Filled Grid, or Unfilled Grid Deck Composite with Reinforced Concrete Slab on Steel or Concrete Beams: Concrete T-	a, e, k and also i, j if sufficiently connected to act as a unit	Lever Rule	$g = e\, g_{interior}$ $e = 0.6 + \frac{d_e}{10}$	$-1.0 \le d_e \le 5.5$
			Lever Rule	$N_b = 3$

Notes: distribution factor for the exterior beam shall not be taken to be less than that which would be obtained by assuming that the cross-section deflects and rotates as a rigid cross-section (SPECIAL ANALYSIS)

$$R = \frac{N_L}{N_b} + \frac{X_{ext} \sum^{N_L} e}{\sum^{N_b} x^2}$$

Live-Load Distribution Factors

Exterior Girder – *Lever Rule*



Live-Load Distribution Factors
Exterior Girder - *Special Analysis*

$$R = \frac{N_L}{N_b} + \frac{X_{ext} \sum^{N_L} e}{\sum^{N_b} x^2}$$

Eq. (C4.6.2.2.2d-1)

R = reaction on exterior beam in terms of lanes

N_L = number of loaded lanes under consideration

e = eccentricity of a lane from the center of gravity of the pattern of girders (ft)

x = horizontal distance from the center of gravity of the pattern of girders to each girder (ft)

X_{ext} = horizontal distance from the center of gravity of the pattern of girders to the exterior girder (ft)

N_b = number of beams or girders

QUESTIONS?

U.S. Department of Transportation
Federal Highway Administration

Unified Straight and Curved Steel Girder Design Specifications

2005

Introduction
Unified Steel Specifications

Straight

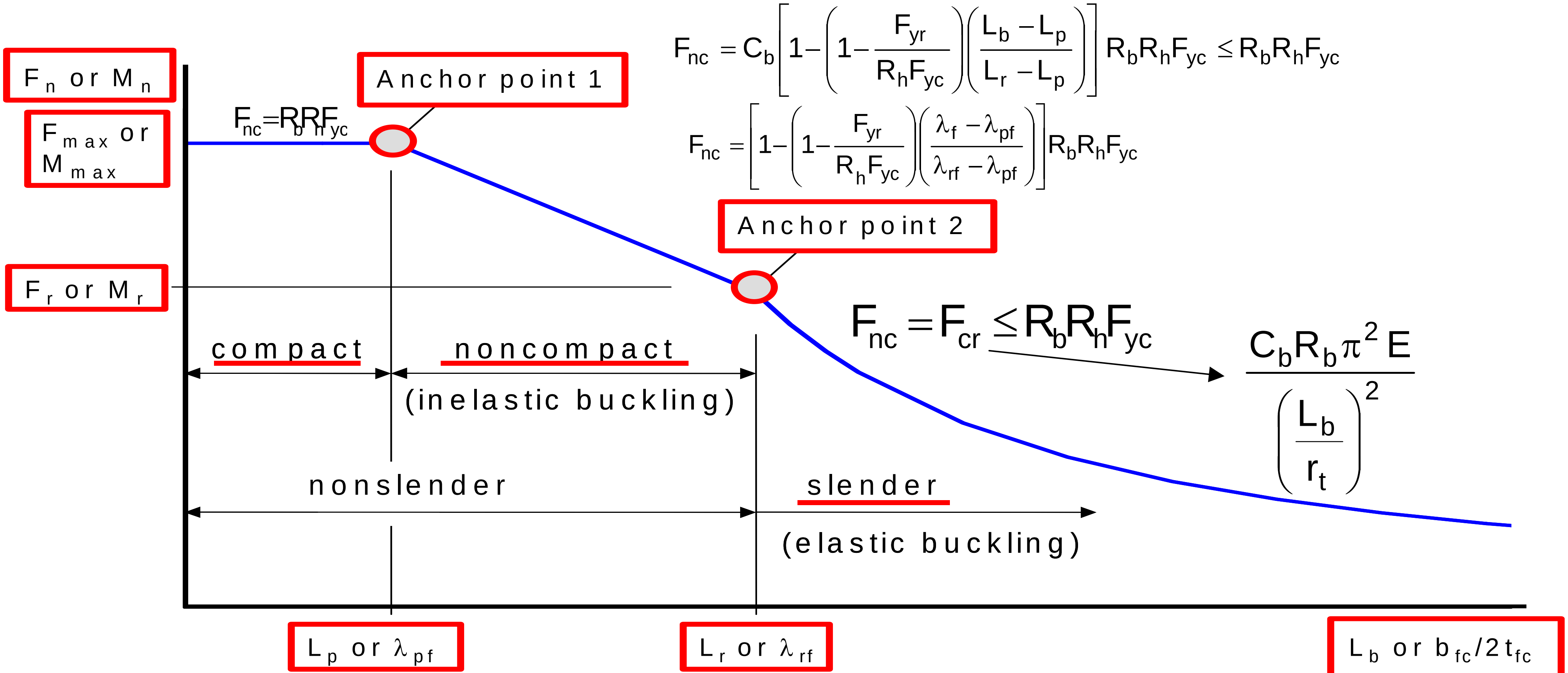
Curved

One Specs!

Fundamentals

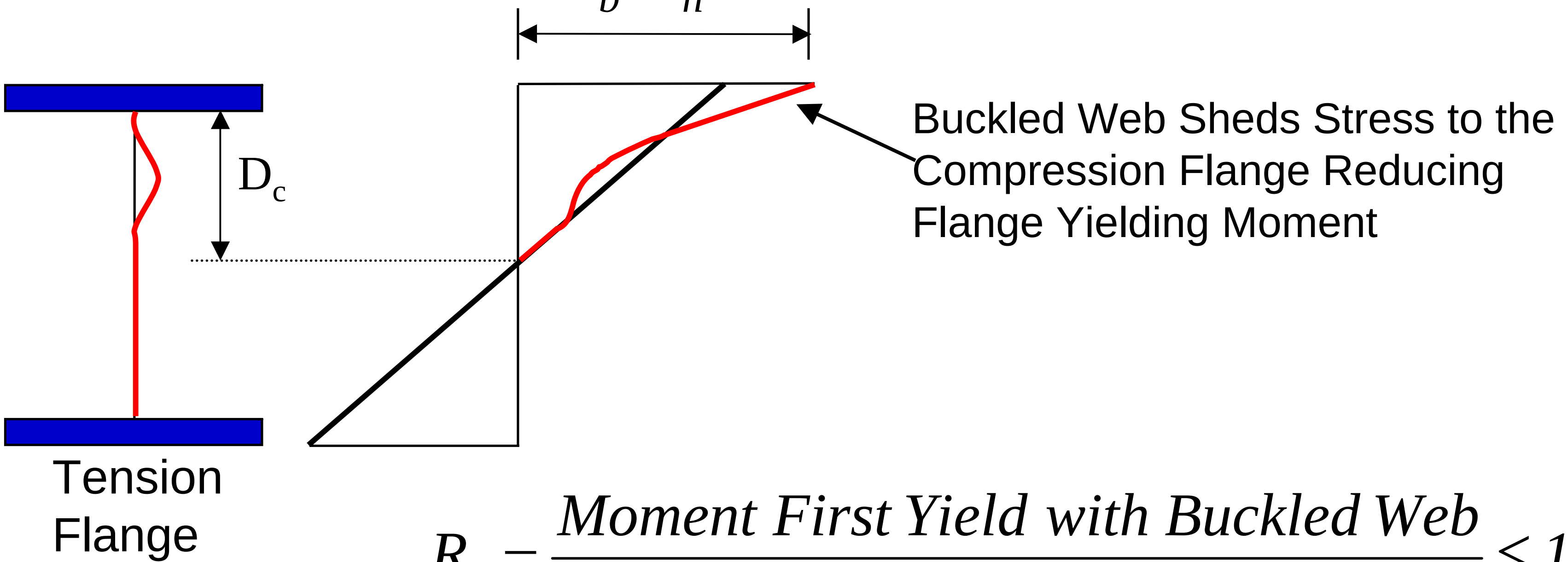
- ✓ Primary-Strength Flexural & Shear Effects
- ✓ Lateral Flange Effects
    - ✓ Differential Deflection Effects
    - ✓ Torsion Effects
    - ✓ Lateral Force Effects
    - ✓ Second-Order Effects
- ✓ Cross Frame Forces

FLB and LTB


F n or M n
F max or M max
F r or M r
Fnc=RbRhFyc
Anchor point 1
Anchor point 2
$F_{nc} = C_b \left[1 - \left(1 - \frac{F_{yr}}{R_h F_{yc}}\right)\left(\frac{L_b - L_p}{L_r - L_p}\right)\right] R_b R_h F_{yc} \le R_b R_h F_{yc}$
$F_{nc} = \left[1 - \left(1 - \frac{F_{yr}}{R_h F_{yc}}\right)\left(\frac{\lambda_f - \lambda_{pf}}{\lambda_{rf} - \lambda_{pf}}\right)\right] R_b R_h F_{yc}$
$F_{nc} = F_{cr} \le R_b R_h F_{yc}$
$\frac{C_b R_b \pi^2 E}{\left(\frac{L_b}{r_t}\right)^2}$
compact
noncompact
(inelastic buckling)
nonslender
slender
(elastic buckling)
L p or λ pf
L r or λ rf
L b or b fc/2t fc

Post Web Buckling Strength

$$\frac{f_{bu}}{R_b R_h} \leq \phi_f F_{yf} \Rightarrow f_{bu} \leq \phi_f R_b R_h F_{yf}$$



$$R_b = \frac{\textit{Moment First Yield with Buckled Web}}{M_y = F_y S} \leq 1.0$$

$$R_b = 1 - \left(\frac{a_{wc}}{1200 + 300\, a_{wc}}\right)\left(\frac{2 D_c}{t_w} - \lambda_{rw}\right) \leq 1.0$$

Fundamentals

- ✓ Primary Flexural & Shear Effects
- ✓ Lateral Flange Effects
  - ✓ Differential Deflection Effects
  - ✓ Torsion Effects
  - ✓ Lateral Force Effects
  - ✓ Second-Order Effects
- ✓ Cross Frame Forces

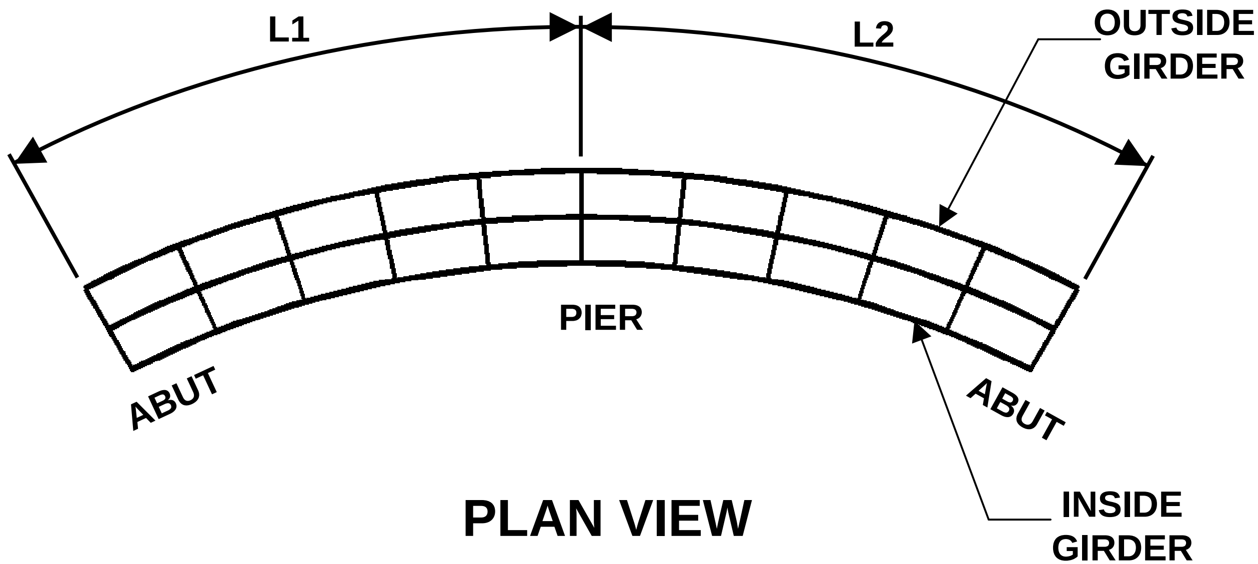
Fundamentals

- ✓ Primary Flexural & Shear Effects
- ✓ Lateral Flange Effects
  - ✓ **Differential Deflection Effects**
  - ✓ Torsion Effects
  - ✓ Lateral Force Effects
  - ✓ Second-Order Effects
- ✓ Cross Frame Forces

Differential Load/Deflection Effects

- Outside girder carries more load
- Vertical Deflection is not equal between adjacent girders

=> Torsional Effects on Girders, Lateral Flange Bending, and Affects fit-up during construction

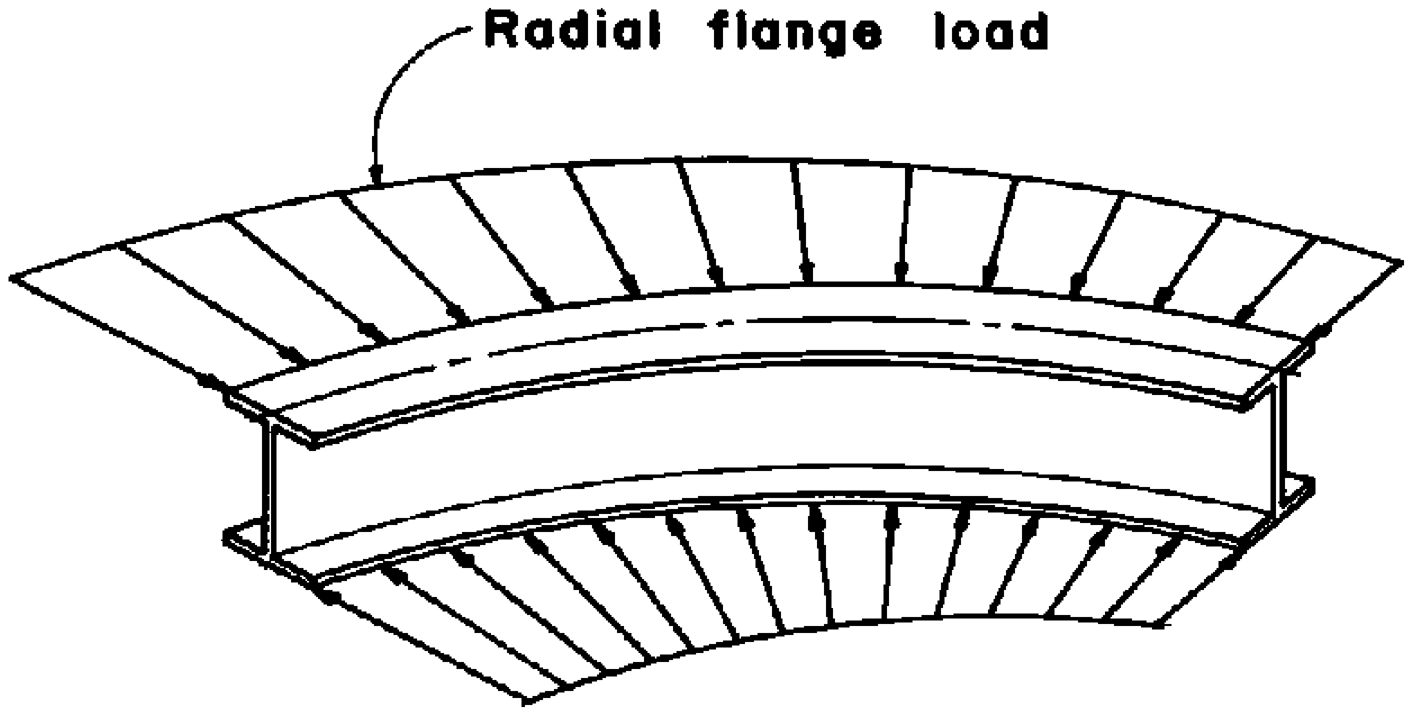


Fundamentals

- ✓ Primary Flexural & Shear Effects
- ✓ Lateral Flange Effects
  - ✓ Differential Deflection Effects
  - ✓ Torsion Effects
  - ✓ Lateral Force Effects
  - ✓ Second-Order Effects
- ✓ Cross Frame Forces

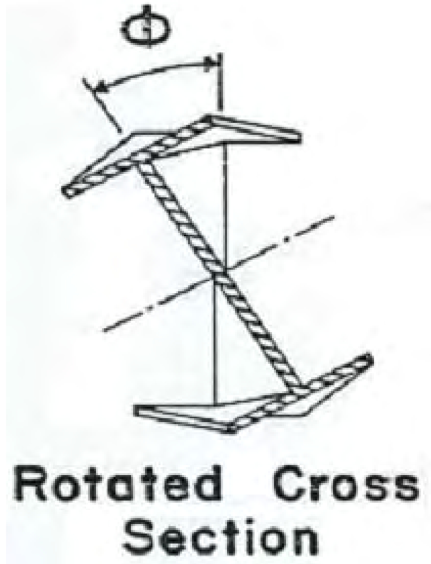
Torsion Effects

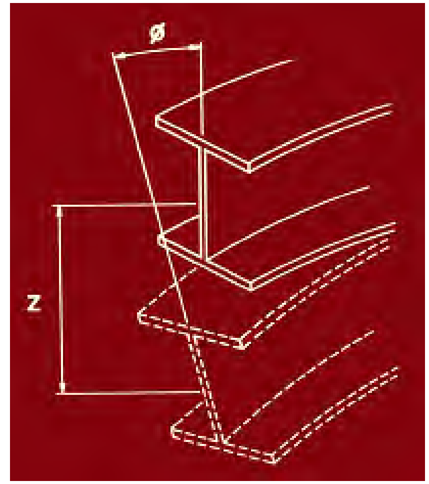
- ✓ **Deformations**
- ✓ **Stresses**



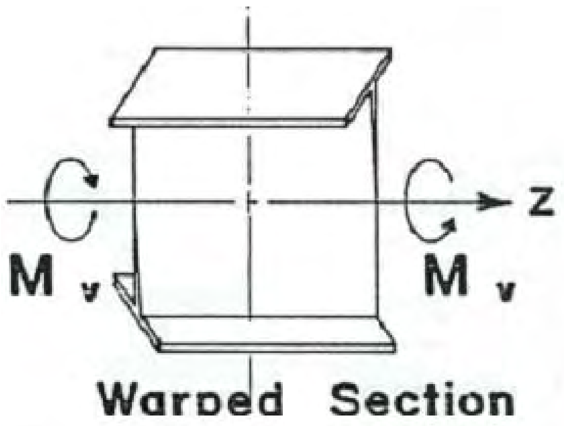
Torsion Deformations

- ✓ **Twisting**





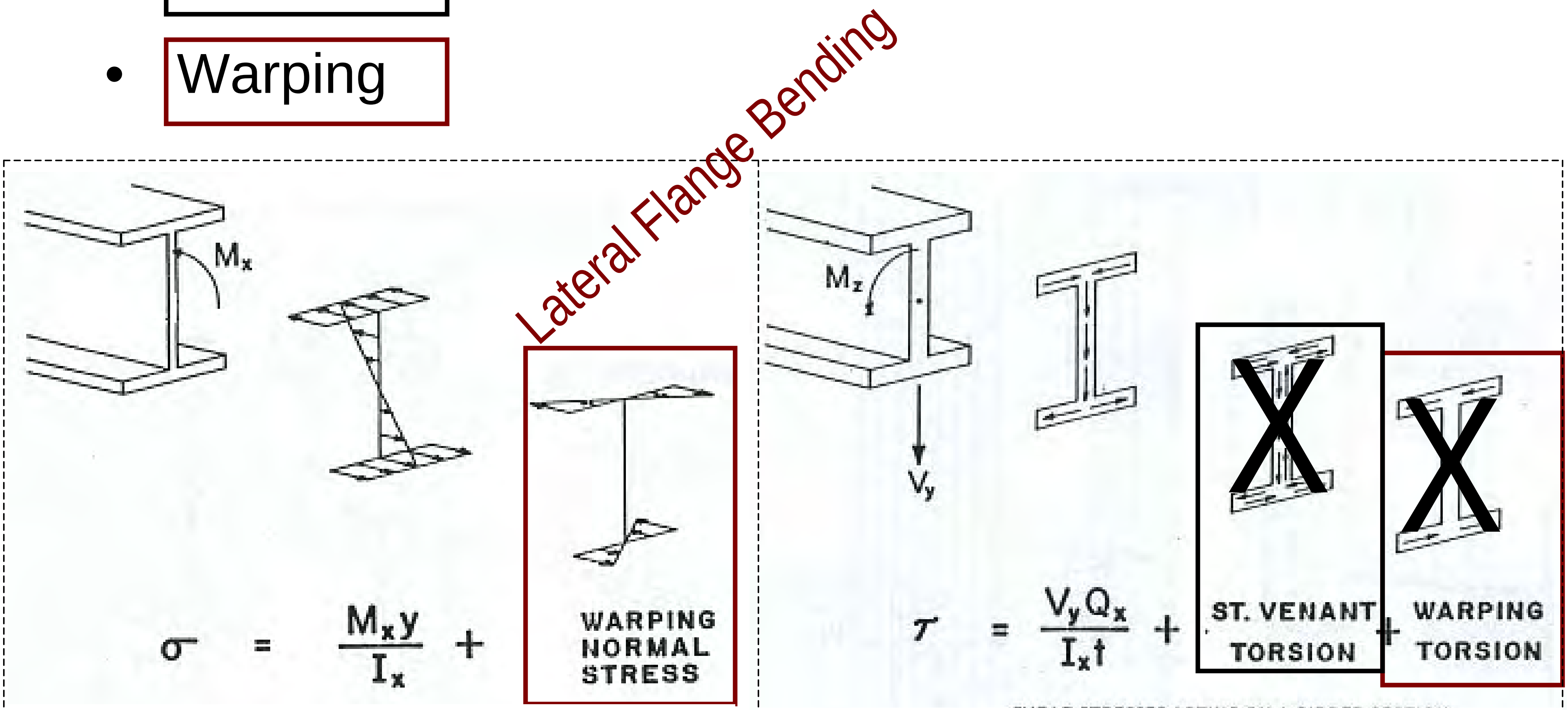
- ✓ **Warping**



=> <u>Affect fit-up during construction</u>

Torsion Stresses

- St. Venant
- Warping



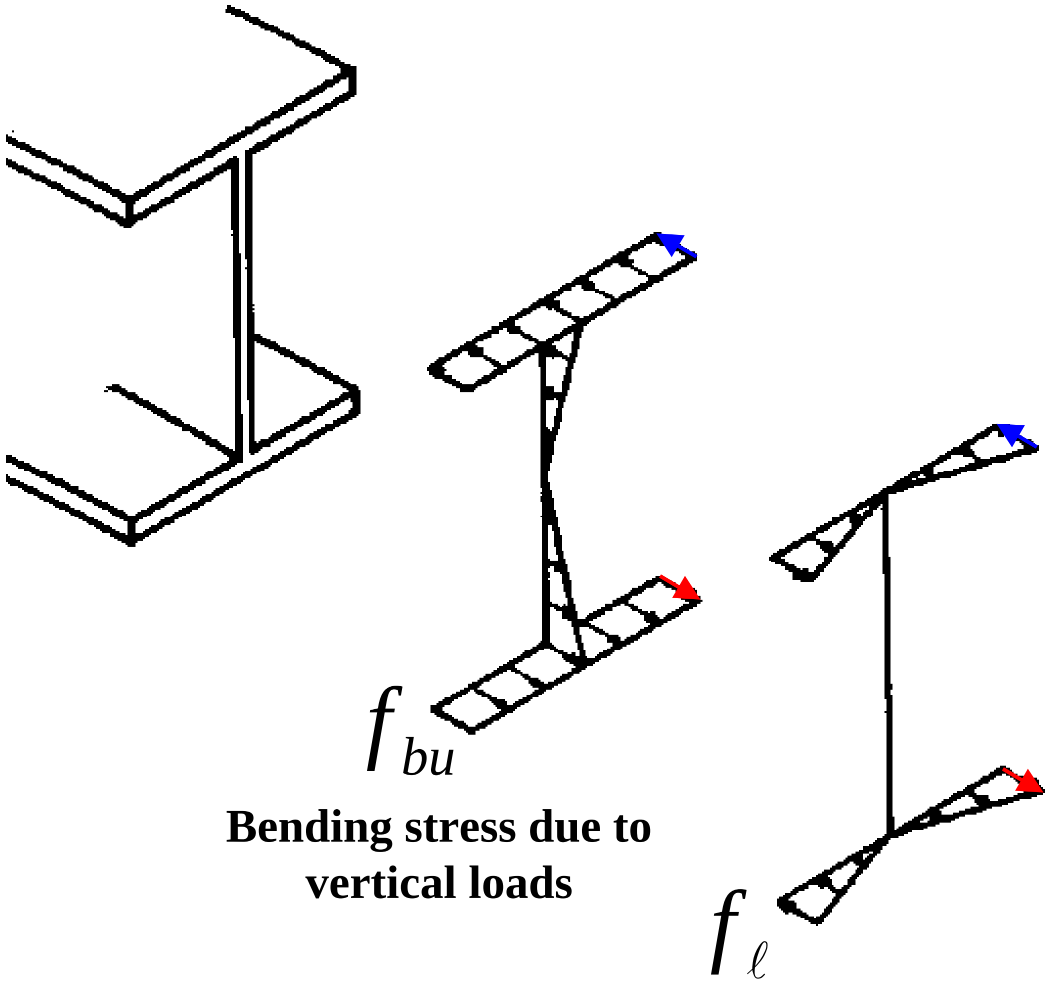
Normal Stresses

Shear Stresses

Fundamentals

- ✓ Primary Flexural & Shear Effects
- ✓ Lateral Flange Effects
  - ✓ Differential Deflection Effects
  - ✓ Torsion Effects
  - ✓ Lateral Force Effects
  - ✓ Second-Order Effects
- ✓ Cross Frame Forces

Lateral Force Effects

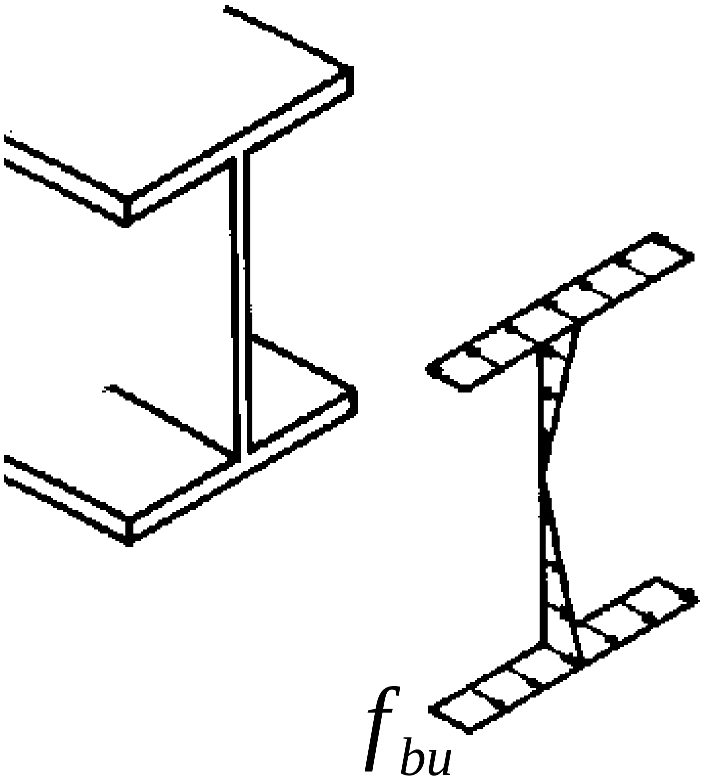


Bending stress due to vertical loads

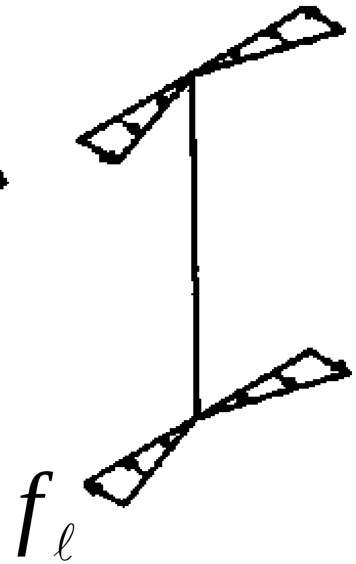
flange lateral bending stress due to wind, skew, or curvature

$$f_{bu} \pm ?\ f_\ell \leq F_r$$

=> Lateral Force Effects & “One-Third” Rule



Bending stress due to vertical loads



flange lateral bending stress due to wind, skew, or curvature

$$f_{bu} + \frac{1}{3} f_{\ell} \leq \phi_f F_{nc}$$

$$f_{bu} + \frac{1}{3} f_{\ell} \leq \phi_f F_{yt}$$

Implementation of "One-Third" Rule

Discretely Braced Flanges

$$f_{bu} + \frac{1}{3} f_{\ell} \leq F_r$$ Strength Limit State, Constructibility-Compression

$$M_u + \frac{1}{3} f_{\ell} S_x \leq M_r$$ Strength Limit State – Compact Straight

$$f_{bu} + f_{\ell} \leq F_r$$ Constructibility Yielding $\frac{1}{3} \Rightarrow 1$

$$f_{bu} + \frac{1}{2} f_{\ell} \leq F_r$$ Service Limit State $\frac{1}{3} \Rightarrow \frac{1}{2}$

Continuously Braced Flanges

$$f_{bu} \leq F_r$$ ALL L.S., Continuously Braced Flanges, $f_{\ell} = 0$

Implementation of "One-Third" Rule

Discretely Braced Flanges

$$f_{bu} + \frac{1}{3} f_\ell \le F_r$$ Strength Limit State, Constructibility-Compression

$$M_u + \frac{1}{3} f_\ell S_x \le M_r$$ Strength Limit State – Compact Straight

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$$f_{bu} \le F_r$$ ALL L.S., Continuously Braced Flanges, $f_\ell = 0$

Implementation of "One-Third" Rule

Discretely Braced Flanges

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Implementation of "One-Third" Rule

Discretely Braced Flanges

$$f_{bu} + \frac{1}{3} f_\ell \leq F_r$$ Strength Limit State & Constructibility-Compression

$$M_u + \frac{1}{3} f_\ell S_x \leq M_r$$ Strength Limit State – Compact Straight

$$f_{bu} + f_\ell \leq F_r$$ Constructibility Yielding $\frac{1}{3} \Rightarrow 1$

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Continuously Braced Flanges

$$f_{bu} \leq F_r$$ ALL L.S., Continuously Braced Flanges, $f_\ell = 0$

Implementation of "One-Third" Rule

Discretely Braced Flanges

$$f_{bu} + \frac{1}{3} f_{\ell} \le F_r$$ Strength Limit State, Constructibility-Compression

$$M_u + \frac{1}{3} f_{\ell} S_x \le M_r$$ Strength Limit State – Compact Straight

$$f_{bu} + f_{\ell} \le F_r$$ Constructibility Yielding $\frac{1}{3} \Rightarrow 1$

$$f_{bu} + \frac{1}{2} f_{\ell} \le F_r$$ Service Limit State $\frac{1}{3} \Rightarrow \frac{1}{2}$

Continuously Braced Flanges

$$f_{bu} \le F_r$$ ALL L.S., Continuously Braced Flanges, $f_{\ell} = 0$

Fundamentals

- ✓ Primary Flexural & Shear Effects
- ✓ Lateral Flange Effects
  - ✓ Differential Deflection Effects
  - ✓ Torsion Effects
  - ✓ Lateral Force Effects
  - ✓ Second-Order Effects
- ✓ Cross Frame Forces (Primary Members)

Second-Order Effects (Art. 6.10.1.6)

- If $$L_b > 1.2 L_p \sqrt{\frac{C_b R_b}{f_{bu} / F_{yc}}}$$

  Second-order compression-flange lateral bending stresses may be approximated by amplifying first-order value:

$$f_\ell = \left(\frac{0.85}{1 - \frac{f_{bu}}{F_{cr}}} \right) f_{\ell 1} \geq f_{\ell 1} \qquad F_{cr} = \frac{C_b R_b \pi^2 E}{\left(\frac{L_b}{r_t} \right)^2}$$

Fundamentals

- ✓ **Primary Flexural & Shear Effects**
- ✓ **Lateral Flange Effects**
    - ✓ **Differential Deflection Effects**
    - ✓ **Torsion Effects**
    - ✓ **Lateral Force Effects**
    - ✓ **Second-Order Effects**
- ✓ **Cross Frame Forces (*Primary Members*)**

SUMMARY
Unified Steel Specifications

Straight

Curved

One Specs!

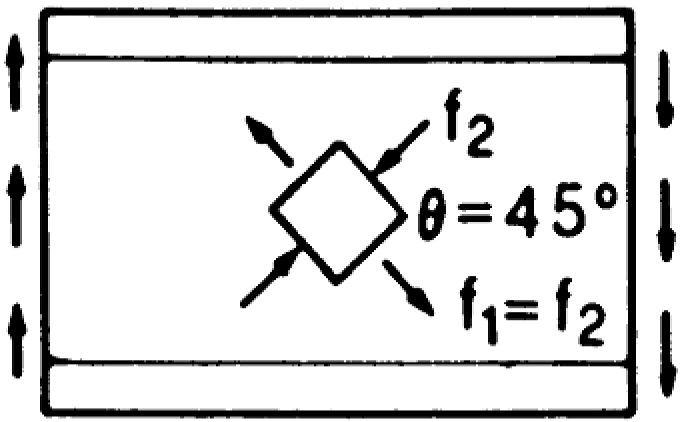
Enough Said!

Shear Design

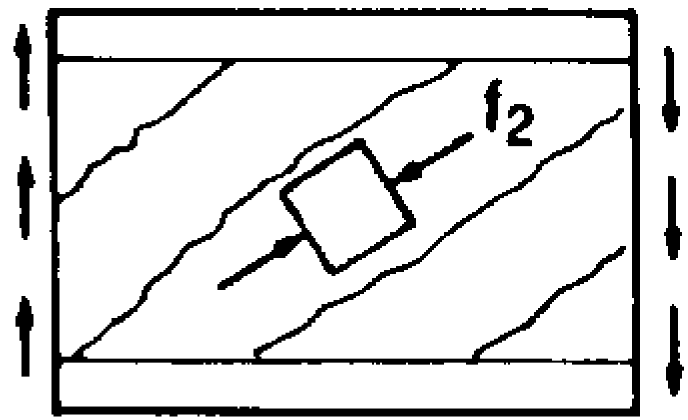
Based on

Sectional Model/Modified Compression Field Theory

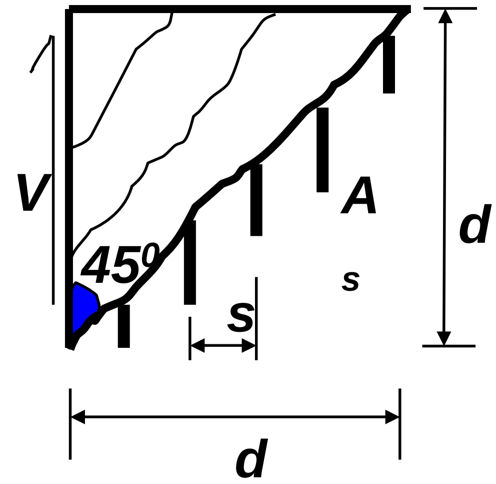
Traditional Shear Design Method



1 - Before Cracking



2 - After Cracking

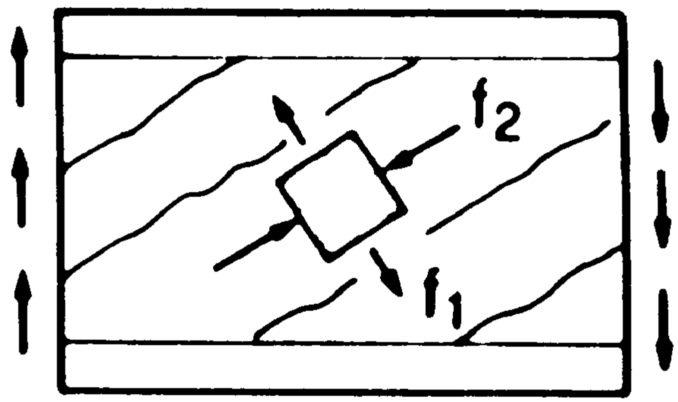


$$V_s = \frac{A_s f_y}{s} d$$

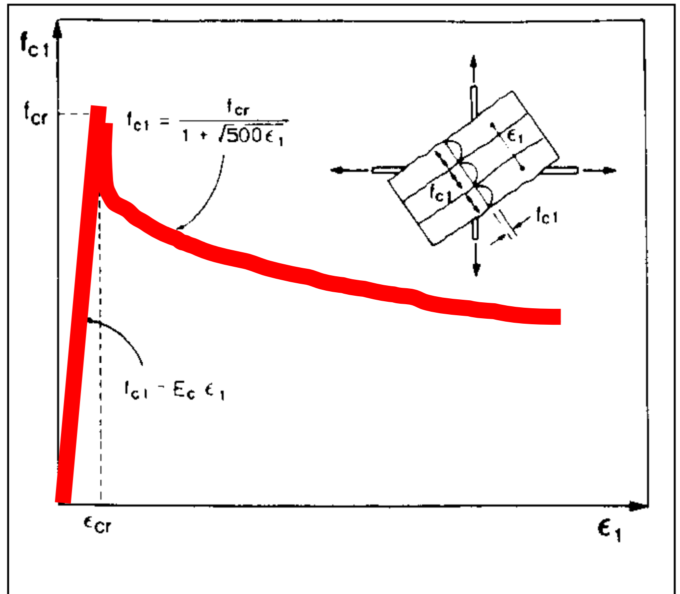
Modified Compression Theory

Diagonal Compression, Tension in Cracked Concrete

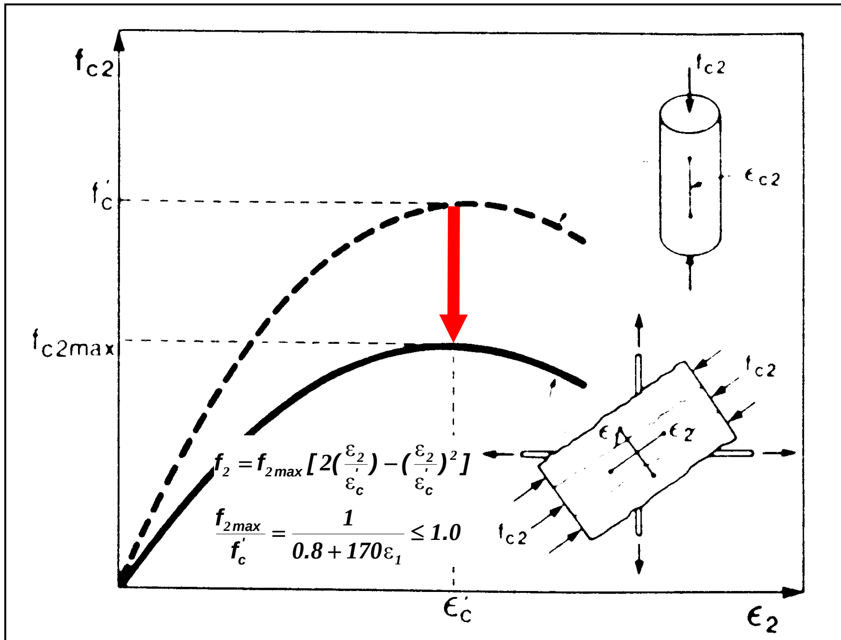
Variable Angle Truss Analogy



Modified compression field theory, $f_1 \neq 0$



Average stress-strain relationship for cracked concrete in tension



5.8.3.3 Nominal Shear Resistance

$$V_n = V_c + V_s + V_p \qquad \textbf{(5.8.3.3-1)}$$

$$V_n = 0.25 f_c' b_v d_v + V_p \qquad \textbf{(5.8.3.3-2)}$$

where:

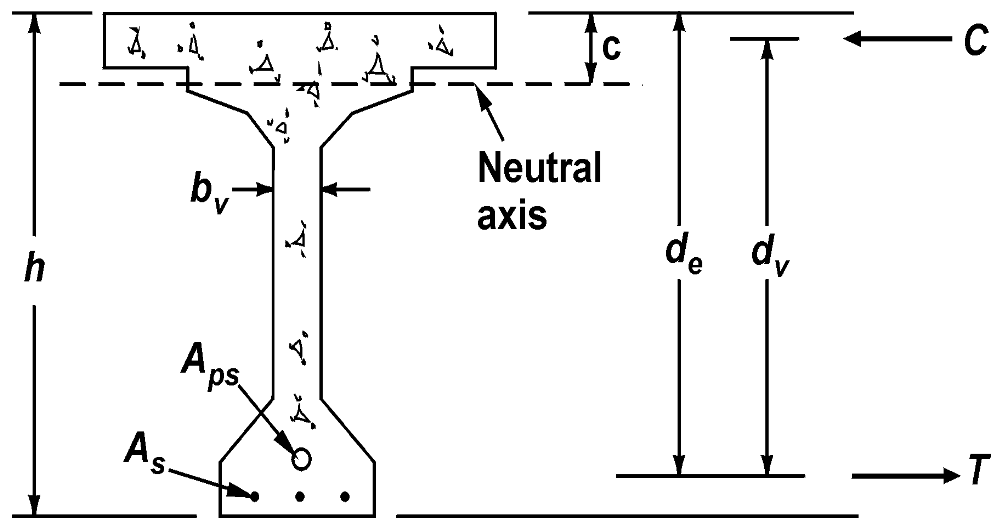
$$V_c = 0.0316 \beta \sqrt{f_c'} \; b_v d_v \qquad \textbf{(5.8.3.3-3)}$$

$$\boldsymbol{\beta} = \frac{f_1 \cot\theta}{\sqrt{f_c'}} \le limit$$

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

Factors for Determining β and θ (v_u and ε_x)

$$v_u = \frac{V_u - \phi V_p}{\phi b_v d_v} \quad \textbf{(5.8.2.9-1)}$$



b_v = effective web width

d_v = effective shear depth; distance between the resultants of the tensile and compressive forces due to flexure $\geq$ the greater of 0.9 de or 0.72h

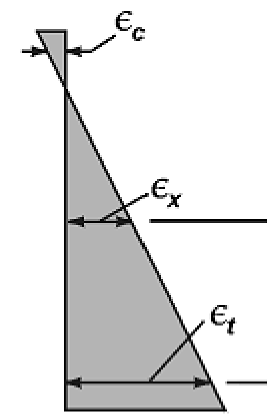
ϕ = resistance factor for shear specified in Article 5.5.4.2

Strain ε_x in Tension Chord

If the section contains at least the minimum transverse reinforcement:

$$\varepsilon_x = \frac{\varepsilon_t + \varepsilon_c}{2}$$

0



$$\varepsilon_x = \frac{\left(\frac{M_u}{d_v} + 0.5N_u + 0.5(V_u - V_p)\cot\theta - A_{ps} f_{po}\right)}{2(E_s A_s + E_p A_{ps})}$$ ***(5.8.3.4.2-1)***

where:

A_s ,A_{ps} = area of non-prestressed, and prestressing steel on the flexural tension side of the member

5.8.3.4 Determination of β and θ

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

Additional Longitudinal Reinforcement to Resist Shear

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

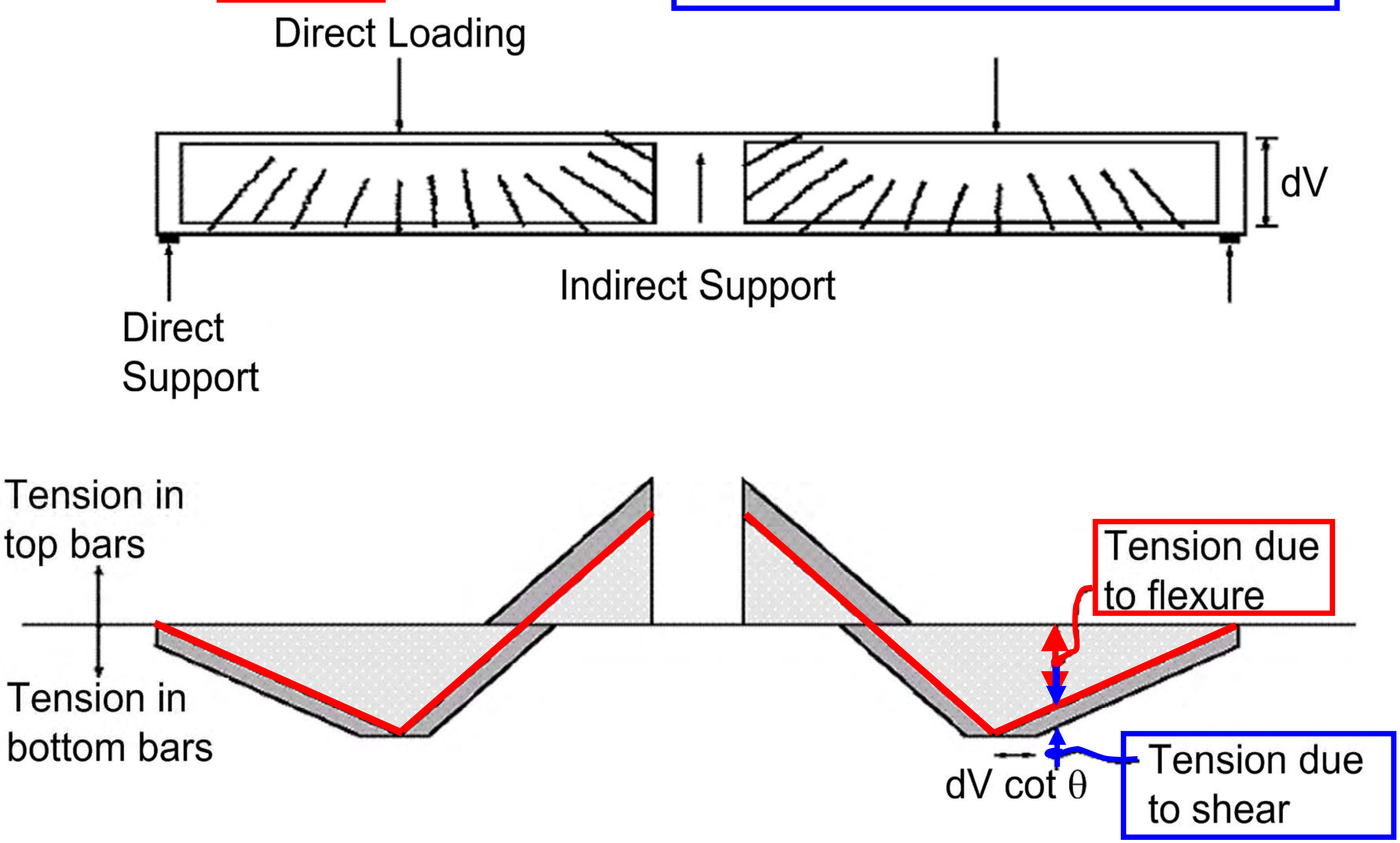
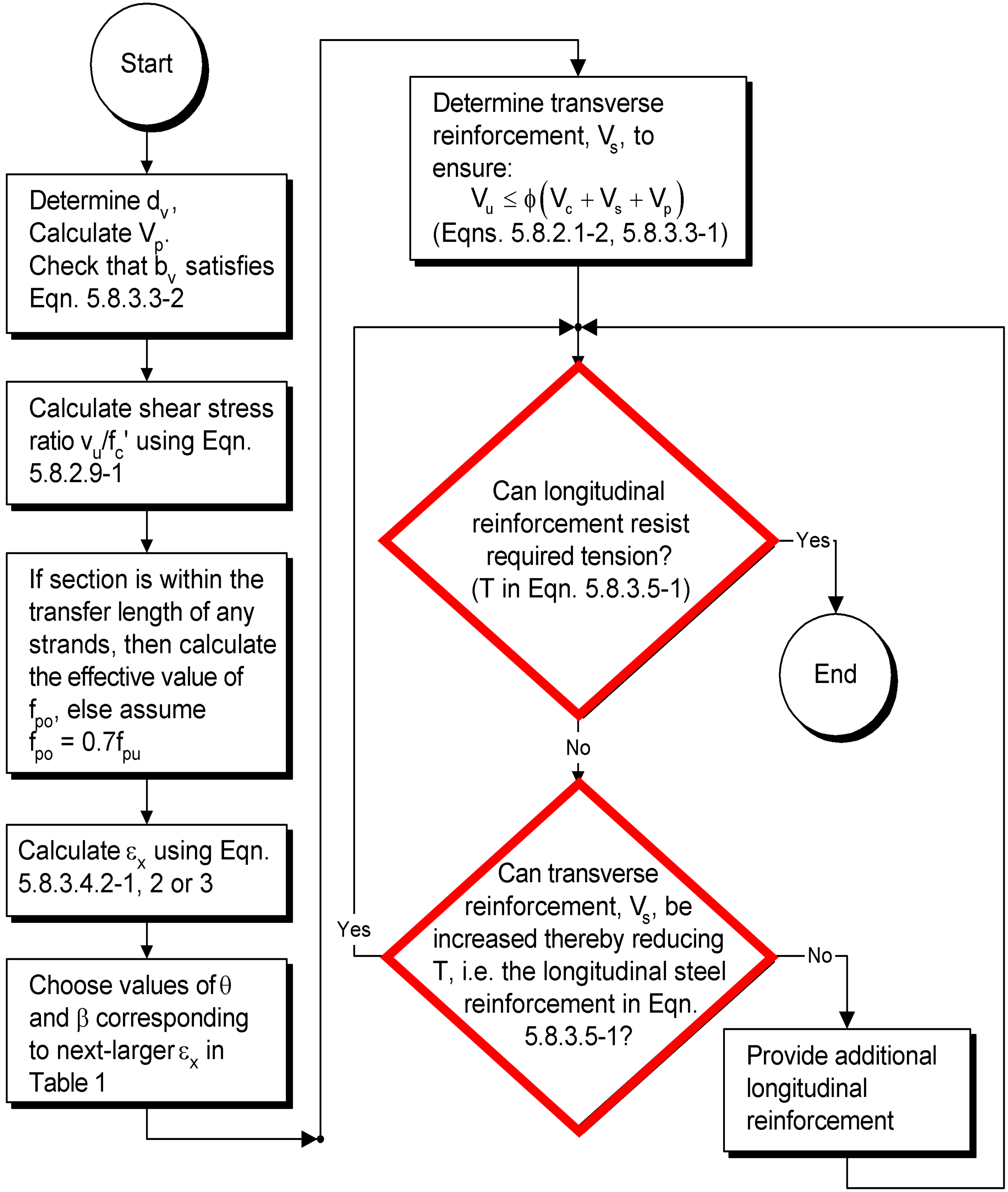


Figure C5.8.3.5-2 Force Variation in Longitudinal Reinforcement Near Maximum Moment Locations.

Figure C5.8.3.4.2-5 Flow Chart for Shear Design of Section Containing at Least Minimum Transverse Reinforcement.



THANK YOU!

Strut-and-Tie Model

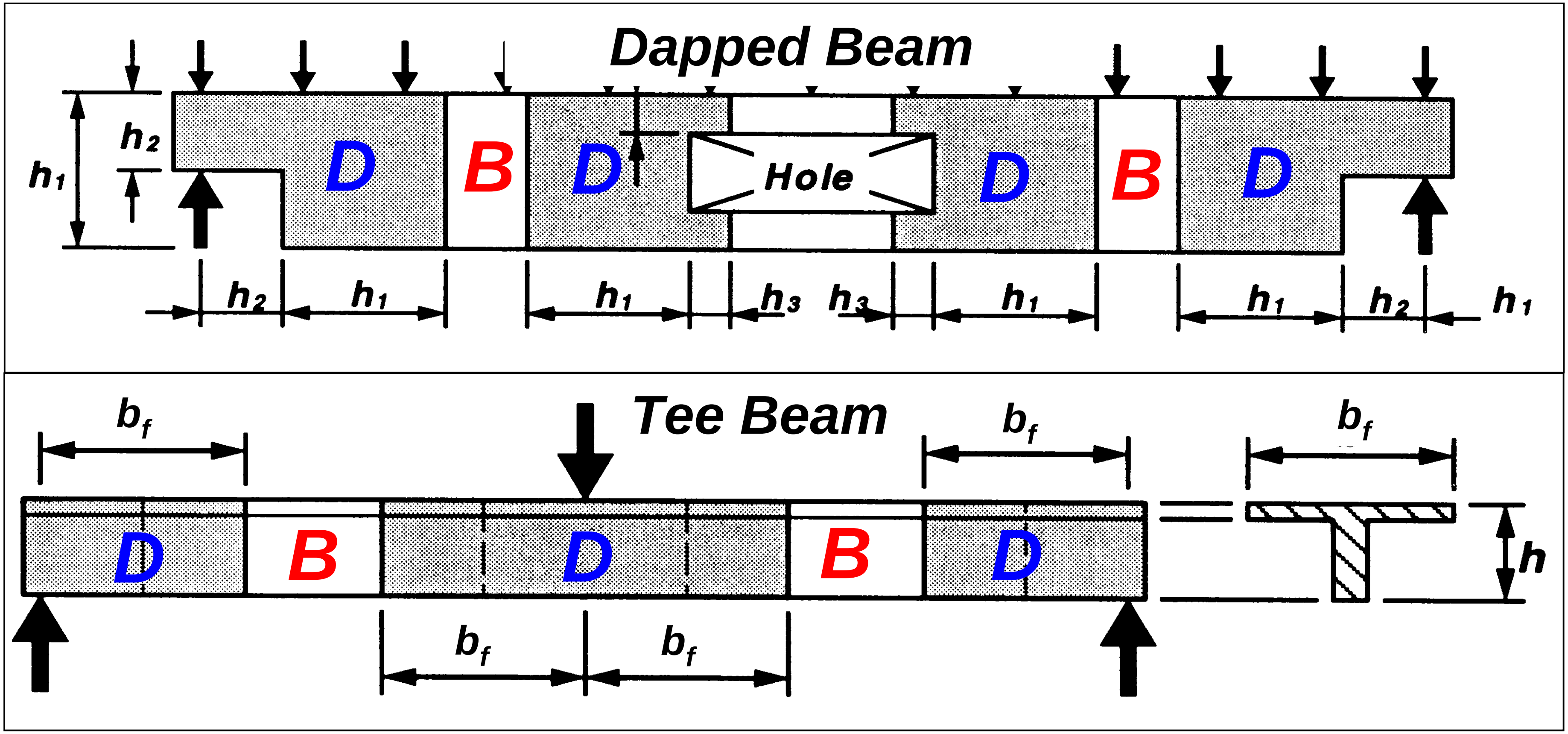
5.8 SHEAR AND TORSION

5.8.1 Design Procedures

5.8.1.2 Regions Near Discontinuities

Where the plane sections assumption of flexural theory is not valid, regions of members shall be designed for shear and torsion using the strut-and-tie model as specified in Article 5.6.3. The provisions of Article 5.13.2 shall apply.

D & B - Regions

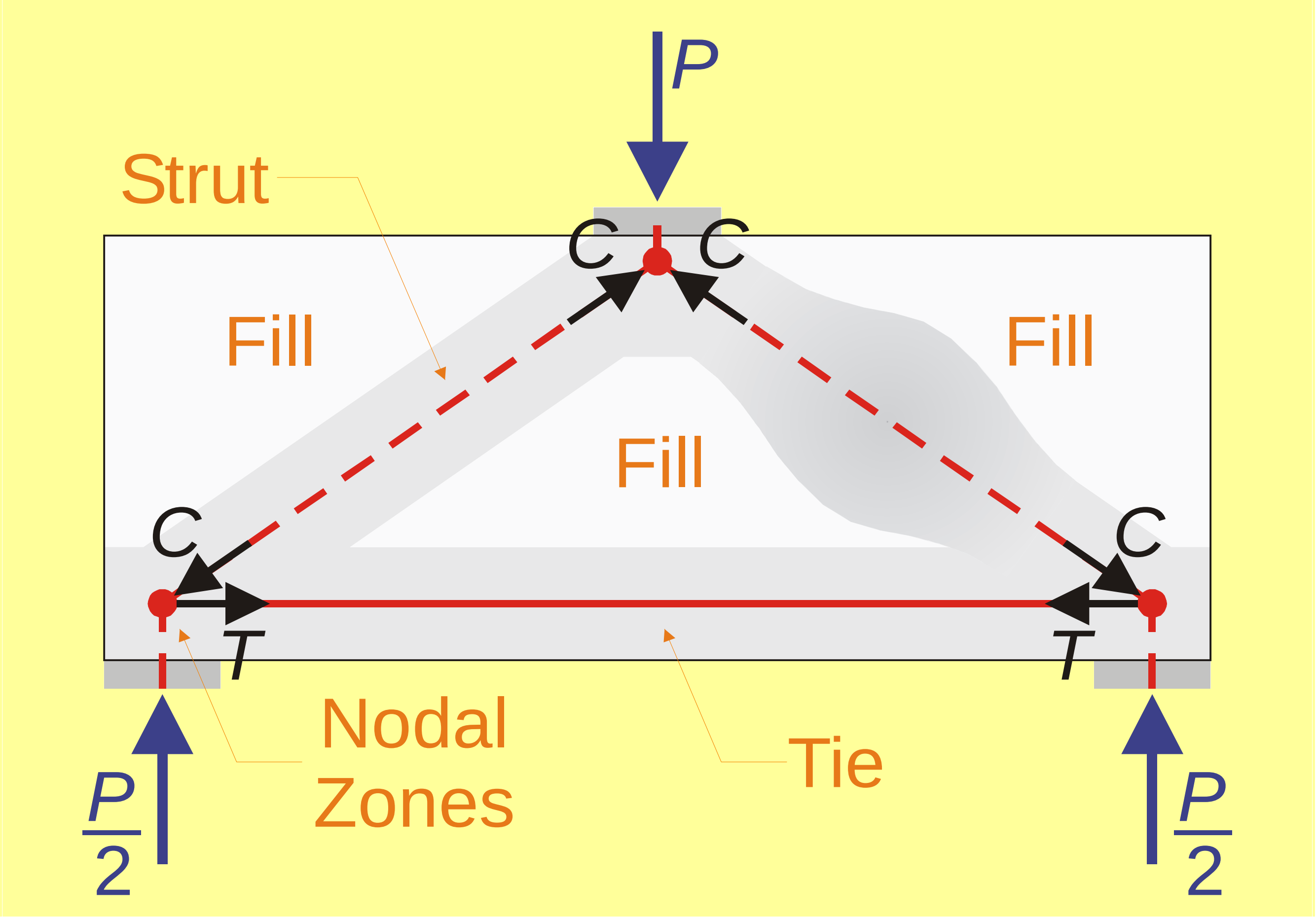


D = Disturbed
Discontinuity
Deep Beam

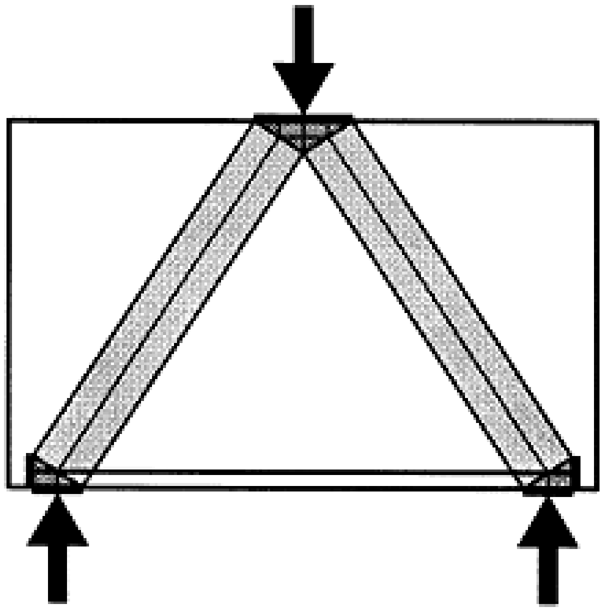
B = Bending
Beam
Bernoulli

Basic Concepts

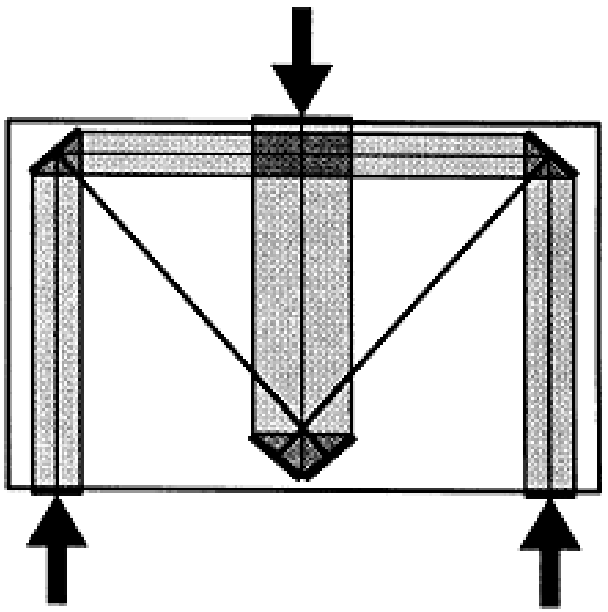
- *Visualize flow of stresses and sketch a strut-tie model to transfer load to the supports, where:*
  - *Compressive forces are resisted by concrete “struts”*
  - *Tensile forces are resisted by steel “ties”*
  - *Struts and ties meet at “nodes”*
- *For best serviceability, the model should follow the elastic flow of forces*



Examples of Good and Poor Strut-and-Tie Models



Good Model



Poor Model

1. Shortest & stiffest path to supports
2. Minimum release of energy (min cracks)

STM Procedures

1. *Visualize flow of stresses*
2. *Sketch an idealized strut-and-tie model*
3. *Select area of ties*
4. *Check nodal zone stresses*
5. *Check strength of struts*
6. *Provide adequate anchorage for ties*
7. *Provide crack control reinforcement*

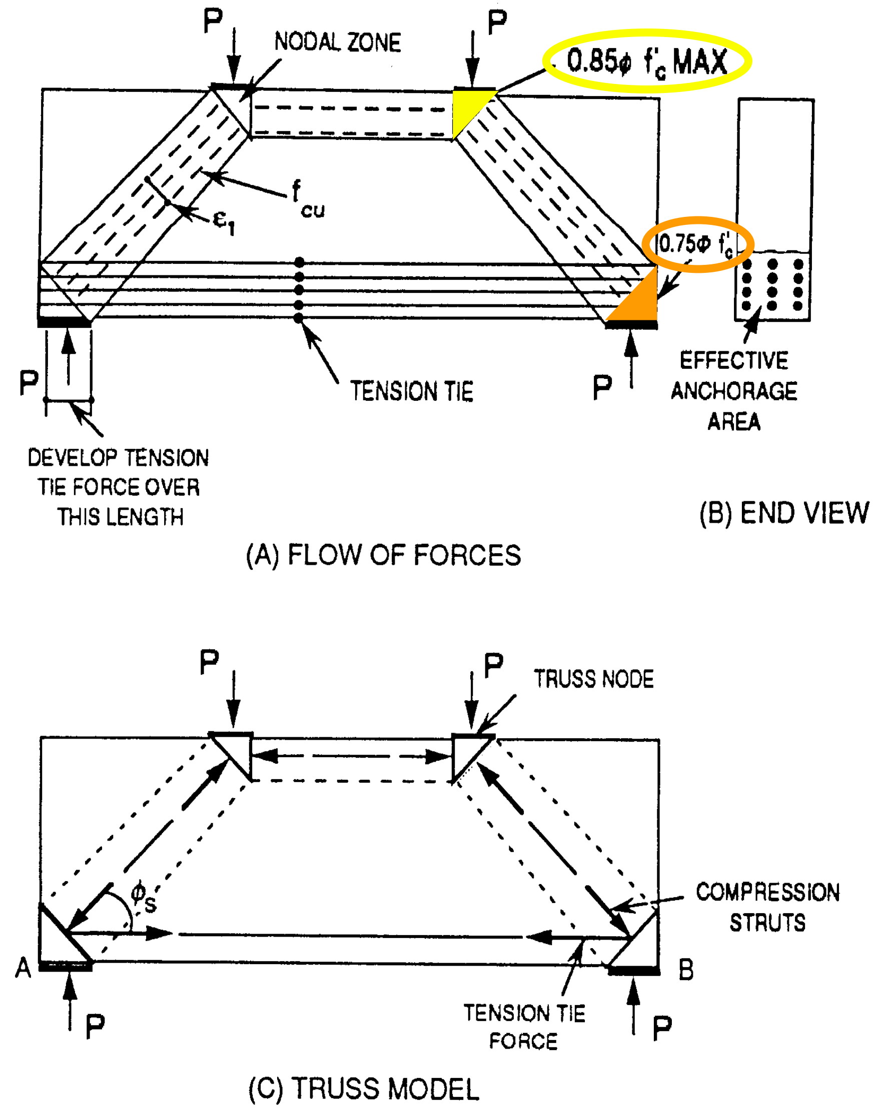


Figure C5.6.3.2-1
Strut-and-Tie Model for a Deep Beam

Strength Limit State for STM

$$P_r = \phi P_n \qquad (5.6.3.2\text{-}1)$$

where:

P_r = Factored resistance of strut or tie

P_n = Nominal resistance of strut or tie

ϕ = Resistance factor for tension or compression (5.5.4.2)

For compression in strut-and-tie models….0.70

For compression in anchorage zones:

normal weight concrete…………………0.80

lightweight concrete……………………0.65

For tension in steel in anchorage zones…...1.00

For tension of reinforced concrete…………0.90

For tension of prestressed concrete………1.00

5.6.3.3 Proportioning of Compressive Struts

5.6.3.3.1 Strength of Unreinforced Strut

$$P_n = f_{cu} A_{cs} \qquad \textbf{(5.6.3.3.1-1)}$$

5.6.3.3.4 Reinforced Strut

$$P_n = f_{cu} A_{cs} + f_y A_{ss} \qquad \textbf{(5.6.3.3.4-1)}$$

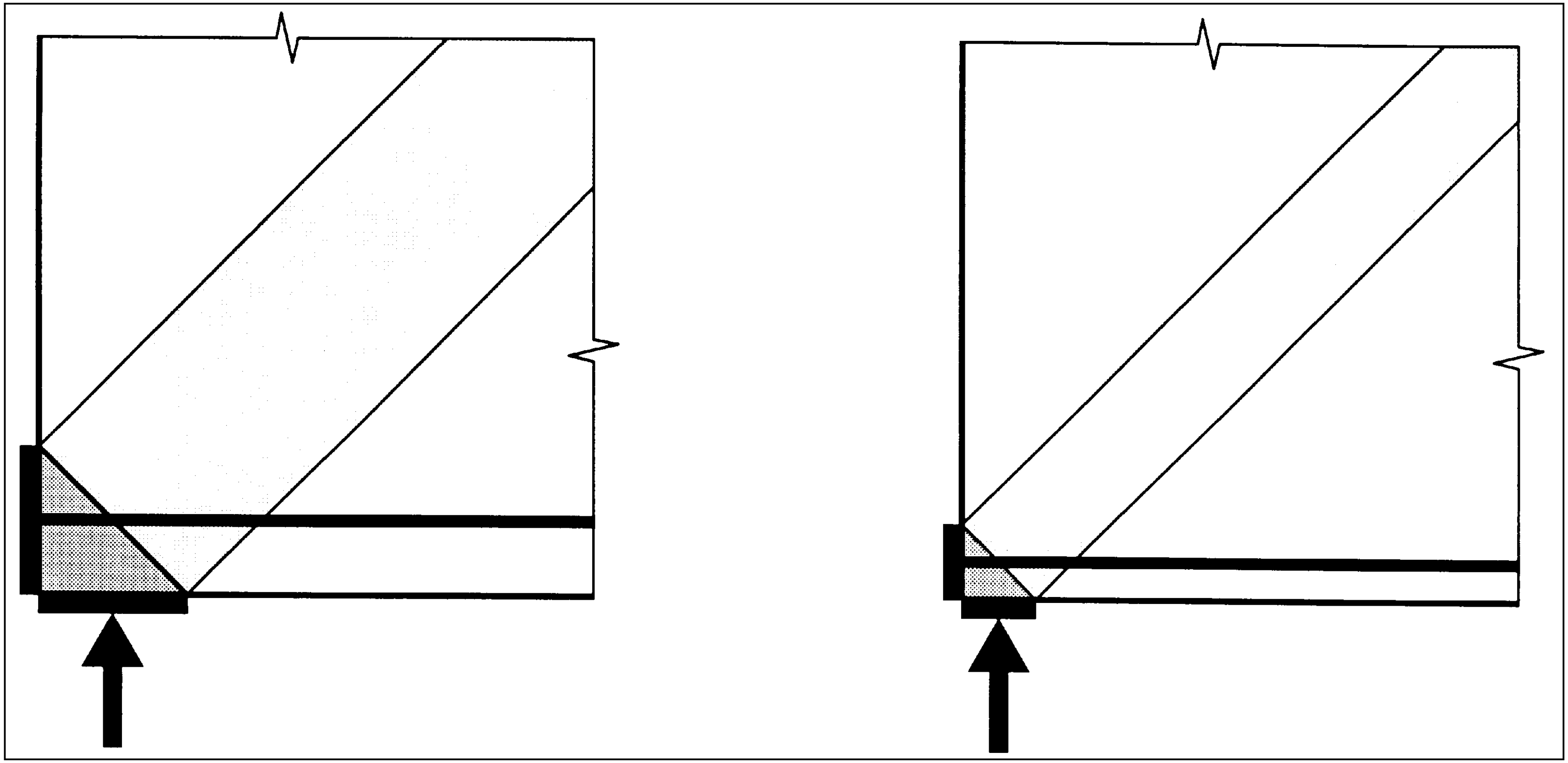
where:

f_{cu} = limiting compressive stress as specified in Article 5.6.3.3.3

A_{cs} = effective cross-sectional area of strut as specified in Article 5.6.3.3.2

A_{ss} = area of reinforcement in the strut

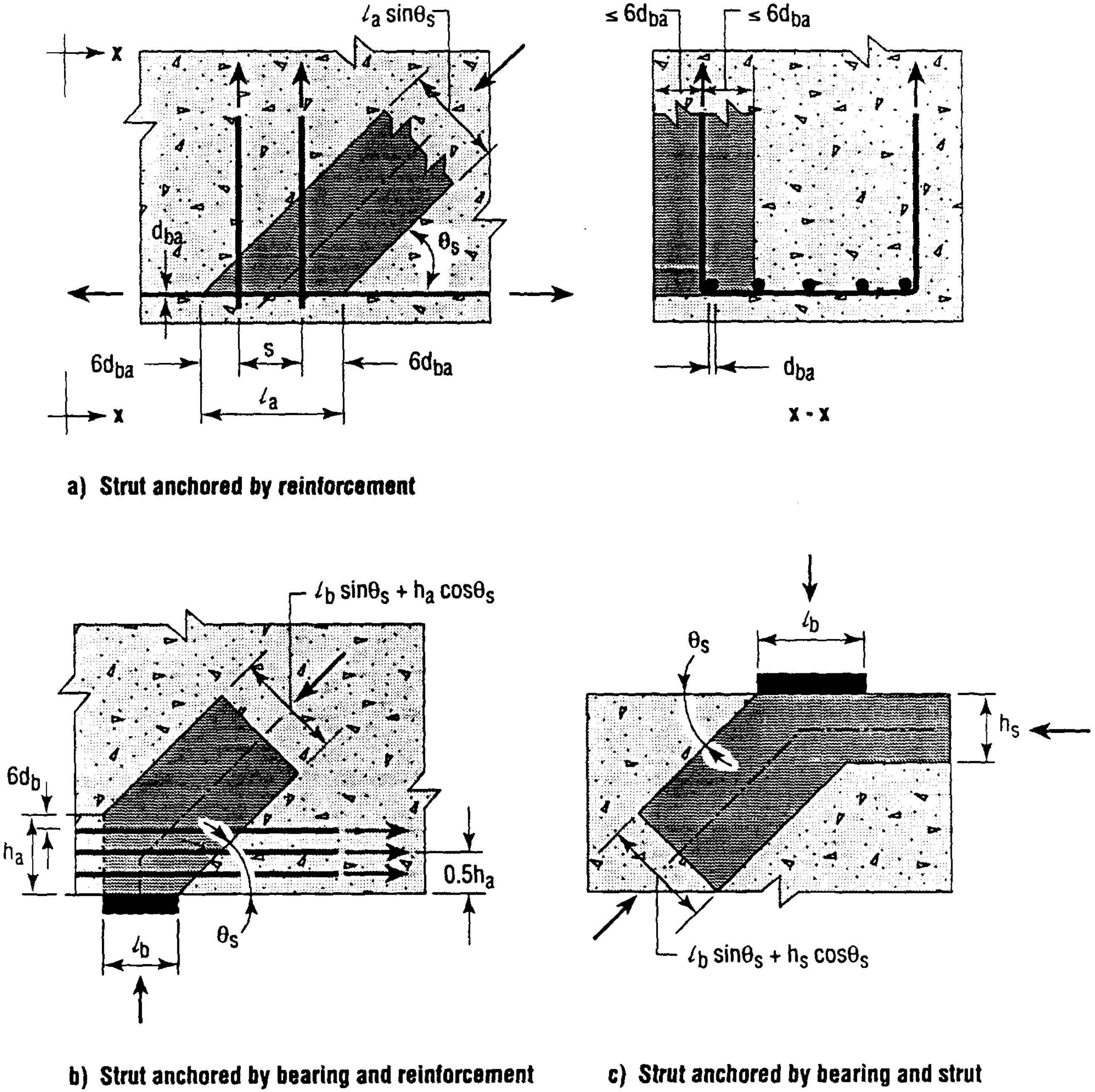
Factors Affecting Size of Strut



Width of the strut is affected by:

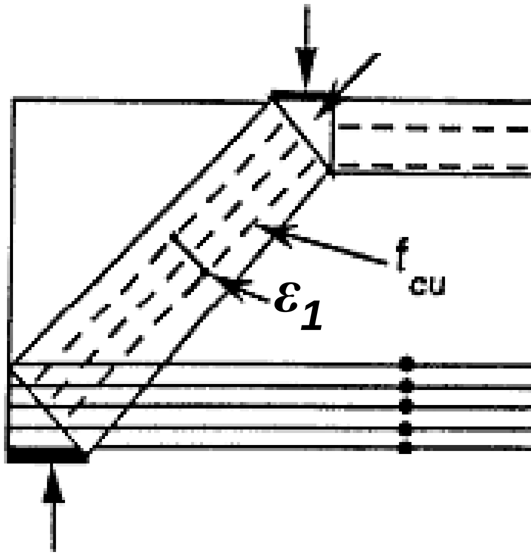
- ***Location and distribution of reinforcement (tie) and its anchorage***
- ***Size and location of bearing***

Figure 5.6.3.3.2-1
Influence of Anchorage Conditions on Effective Cross-Sectional Area of Strut



5.6.3.3.3 Limiting Compressive Stress in Strut

$$f_{cu} = \frac{f'_c}{0.8 + 170\,\varepsilon_1} \leq 0.85\, f'_c$$ ***(5.6.3.3.3-1)***



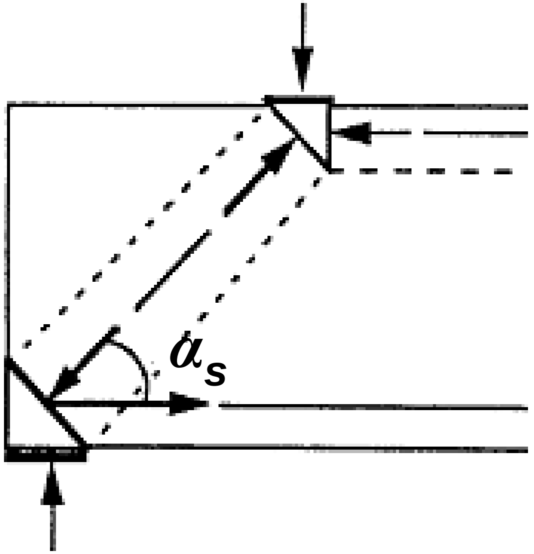
$$\varepsilon_1 = \varepsilon_s + \left(\varepsilon_s + 0.002\right)\cot^2 \alpha_s$$ ***(5.6.3.3.3-2)***

where:

f'_c = specified compressive strength

ε_s = the tensile strain in the concrete in the direction of the tension tie

α_s = the smallest angle between the compressive strut and adjoining tension ties (°)



5.6.3.4.1 Strength of Tie

$$P_n = f_y A_{st} + A_{ps}\left[f_{pe} + f_y \right] \quad \textbf{(5.6.3.4.1-1)}$$

where

f_y = yield strength of mild steel longitudinal reinforcement

A_{st} = total area of longitudinal mild steel reinforcement in the tie

A_{ps} = area of prestressing steel

f_{pe} = stress in prestressing steel due to prestress after losses

5.6.3.5 Proportioning of Node Regions

The concrete compressive stress in the node regions of the strut shall not exceed:

- For node regions bounded by compressive struts and bearing areas: ……… $0.85\,\phi\, f'_c$

- For node regions anchoring a one-direction tension tie: …………………………… $0.75\,\phi\, f'_c$

- For node regions anchoring tension ties in more than one direction:……………… $0.65\,\phi\, f'_c$

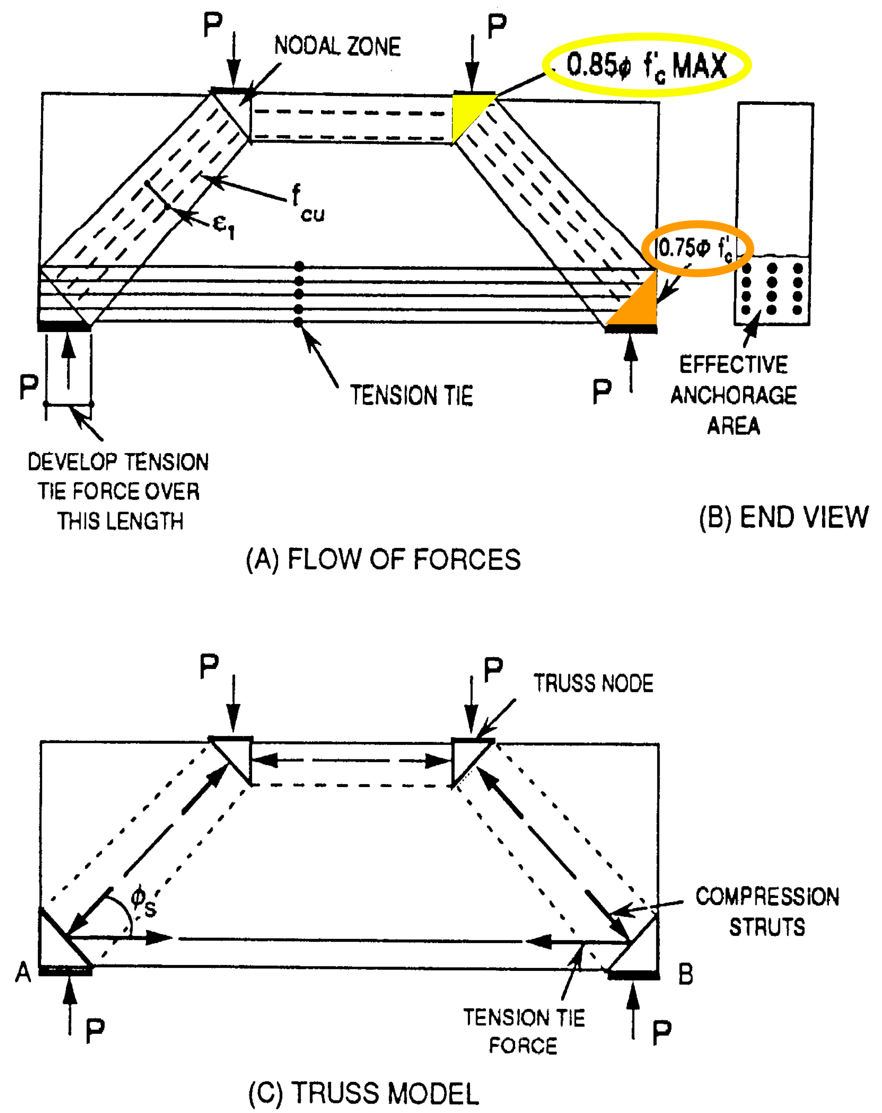


Figure C5.6.3.2-1
Strut-and-Tie Model for a Deep Beam

5.6.3.6 Crack Control Reinforcement

- ***Provide orthogonal grid of reinforcement near each face of D-Region***
- ***Maximum Bar Spacing = 12 in.***
- ***Ratio $A_s / A_g \geq 0.003$ in each of the orthogonal directions***
- ***Crack control reinforcement, located within tie, maybe considered as part of tie***

Questions?